Appointment

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 11/25/2019 9:23:59 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
CC: Stuenkel, David [Stuenkel.David@epa.gov]; David Stuenkel [davidstuenkel@live.com]

Subject: TFI risk assessment review - recurring technical meeting
Attachments: Untitled Attachment; Untitled Attachment; Untitled Attachment; Untitled Attachment; Canceled: TFI risk assessment review - recurring technical meeting
Location: Skype/phone only

Start: 11/27/2019 4:00:00 PM
End: 11/27/2019 5:00:00 PM
Show Time As: Tentative

Recurrence: Weekly
every Wednesday from 11:00 AM to 12:00 PM

All,

I've had to alter my schedule for purposes of child care. It appears that moving our weekly meeting to Wednesday generally works (we'll have to work around Division meetings). Please let me know if this is a problem for you and we'll try another time.

Thnaks.

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CC: Stuenkel, David [Stuenkel.David@epa.gov]

Attachments: TFI_Weekly_updates_agenda_1-7-2019.docx

Start: 1/7/2020 4:00:00 PM
End: 1/7/2020 5:00:00 PM
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Welcome back. Here is today's agenda.

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CC: Stuenkel, David [Stuenkel.David@epa.gov]

Attachments: TFI_Weekly_updates_agenda_2-4-2020.docx

Start: 2/4/2020 4:00:00 PM
End: 2/4/2020 5:00:00 PM
Show Time As: Busy

Recurrence: (none)
every Tuesday from 11:00 AM to 12:00 PM

Agenda attached

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To: Lee, Raymond [Lee.Raymond@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; White, Rick [White.Rick@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
CC: Stuenkel, David [Stuenkel.David@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]

Subject: Canceled: TFI risk assessment review - recurring technical meeting
Attachments: Reclaimer_Scenario_Rn_questions_3-6-2020.docx

Start: 3/10/2020 3:00:00 PM
End: 3/10/2020 4:00:00 PM
Show Time As: Free

Importance: High

Recurrence: (none)

Cancelling today's meeting. We have not received anything new from TFI. We sent a set of questions to TFI on friday regarding the reclaimer scenario, attached.

I'm heads down working on the history of the reclaimer scenario. If anyone has a burning desire to take part of that on, let me know.

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From: Diaz, Charlene [diaz.charlene@epa.gov]
Sent: 10/15/2020 4:30:08 PM
To: Diaz, Charlene [diaz.charlene@epa.gov]; Aquino, Marcos [Aquino.Marcos@epa.gov]; Bhesania, Amy [Bhesania.Amy@epa.gov]; Borries, Samuel [borries.samuel@epa.gov]; Perez, Natalia A. [Perez.Natalia@epa.gov]; Brozowski, George [brozowski.george@epa.gov]; Cooper, Artra [Cooper.Artra@epa.gov]; Davis, Amber [Davis.Amber@epa.gov]; Freed, Rachel [freed.rachel@epa.gov]; Generette, Lloyd [Generette.Lloyd@epa.gov]; Honnellio, Anthony [Honnellio.Anthony@epa.gov]; Hooper, Charles A. [Hooper.CharlesA@epa.gov]; Jablonowski, Eugene [jablonowski.eugene@epa.gov]; McAuley, Jim [mcauley.jim@epa.gov]; Merritt, Steven [Merritt.Steven@epa.gov]; Povetko, Oleg [Povetko.Oleg@epa.gov]; Richards, Jon M. [Richards.Jon@epa.gov]; Schulingkamp, Cristina [schulingkamp.cristina@epa.gov]; Snowbarger, Robert [Snowbarger.Robert@epa.gov]; Wagner, Christine [Wagner.Christine@epa.gov]; Laurita, Matthew [Laurita.Matthew@epa.gov]
CC: Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Griggs, John [Griggs.John@epa.gov]; Clark, Mike S. [Clark.Michael@epa.gov]; Stafford, Andrea [Stafford.Andrea@epa.gov]; Wilds, Edward [Wilds.Edward@epa.gov]; Gomez, Fernando O. [Gomez.Fernando@epa.gov]

Subject: SMR Rulemaking and TFI Press Release Discussion with the Regions
Attachments: TFI response-Comms Plan_09 21 2020 .docx
Location: Microsoft Teams Meeting

Start: 10/19/2020 6:15:00 PM
End: 10/19/2020 7:00:00 PM
Show Time As: Busy

Agenda:

- Roll/Call
- SMR Rulemaking – Lee Veal
- TFI Press Release – Jon Walsh/Tom Peake

Link to TFI Press Release: https://www.epa.gov/newsreleases/epa-approves-use-phosphogypsum-road-construction

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Sent: 10/19/2020 6:10:48 PM
To: Aquino, Marcos [Aquino.Marcos@epa.gov]; Bhesania, Amy [Bhesania.Amy@epa.gov]; Borries, Samuel [borries.samuel@epa.gov]; Perez, Natalia A. [Perez.Natalia@epa.gov]; Brozowski, George [brozowski.george@epa.gov]; Cooper, Artra [Cooper.Artra@epa.gov]; Davis, Amber [Davis.Amber@epa.gov]; Freed, Rachel [freed.rachel@epa.gov]; Generette, Lloyd [Generette.Lloyd@epa.gov]; Honnellio, Anthony [Honnellio.Anthony@epa.gov]; Hooper, Charles A. [Hooper.CharlesA@epa.gov]; Jablonowski, Eugene [jablonowski.eugene@epa.gov]; McAuley, Jim [mcauley.jim@epa.gov]; Merritt, Steven [Merritt.Steven@epa.gov]; Povetko, Oleg [Povetko.Oleg@epa.gov]; Richards, Jon M. [Richards.Jon@epa.gov]; Schulingkamp, Cristina [schulingkamp.cristina@epa.gov]; Snowbarger, Robert [Snowbarger.Robert@epa.gov]; Wagner, Christine [Wagner.Christine@epa.gov]; Laurita, Matthew [Laurita.Matthew@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Griggs, John [Griggs.John@epa.gov]; Clark, Mike S. [Clark.Michael@epa.gov]; Stafford, Andrea [Stafford.Andrea@epa.gov]; Wilds, Edward [Wilds.Edward@epa.gov]

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Attachments: TFI response-Comms Plan_09 21 2020 .docx
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CC: Diaz, Charlene [diaz.charlene@epa.gov]

Subject: TFI Application review
Attachments: Petition for Additional PG Uses 10-11 Submission amended 10-15-19.pdf; Appendix 1.pdf; Appendix 2 PG Risk Assessment- Final amended Oct 15-19.pdf; Appendix 3-Metals Screening Memo.pdf; Appendix 4.pdf; TFI_Gantt_10-28-19.pdf
Location: DCRoomWest1426/OPEI

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End: 10/29/2019 3:30:00 PM
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Let's have a brief meeting to talk about the review of TFI's risk assessment for the use of phosphogypsum in road base, which is attached, along with milestone for the review process.

Draft agenda:

Introduction to the risk assessment
Review timeline and roles
Establish standing meeting times
Discuss processes for sharing information

Thanks,
Jon

ARCADIS Design & Consultancy for natural and built assets

The Fertilizer Institute

RADIOLOGICAL RISK ASSESSMENT IN SUPPORT OF PETITION FOR BENEFICAL USE OF PHOSPHOGYPSUM

October 2019

RADIOLOGICAL RISK ASSESSMENT IN SUPPORT OF PETITION FOR BENEFICIAL USE OF PHOSPHOGYPSUM

Hope Nemickas
Project Environmental Scientist

John Stolys
Senior Environmental Engineer

Les Skoski
Senior Environmental Scientist

Douglas Chambers
National Discipline Leader

Prepared for:

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Our Ref.:

351419

Date:

October 2019

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EXECUTIVE SUMMARY

Phosphogypsum is a by-product of the production of phosphoric acid for the fertilizer industry and contains naturally occurring radioactivity, the same radioactivity that is present in the phosphate ore from which phosphogypsum is derived.

Prior to December 1989, phosphogypsum was considered an item of commerce and sold for agricultural use in central and north Florida and throughout the United States at locations where it was manufactured.

Subsequent Reconsideration

The United States Environmental Protection Agency (EPA) issued the first National Emission Standards for Hazardous Air Pollutants (NESHAP) for radon emissions from phosphogypsum (PG) stacks on December 15, 1989 (54 FR 51654). This NESHAP required that PG be disposed of in stacks. (See legal discussion in the Petition).

The risk assessment described in this report is provided in support of a petition ("Petition") for the beneficial use of By-Product Phosphogypsum ("PG") for the construction of roads. Specifically, three road construction scenarios are considered in the following risk assessment:

1. Road base – PG and soil mixture
2. Road pavement – PG in concrete
3. Road base and pavement – PG in both

The approach to risk assessment for use of PG in road construction is based on EPA guidance and regulation regarding the appropriate risk benchmark for judging reuse of PG. The current risk assessment adopts EPA's long-standing risk management safe level of 3 in 10,000. EPA has previously determined that use of this "risk threshold is consistent with the determination of a 'safe' level (first announced in the NESHAP for certain benzene source categories (54 FR 38044, September 13, 1989))."[1] In 1992, EPA reaffirmed that a 3 in 10,000 risk level was protective of human health and consistent with EPA's long-standing risk management goals.[2] In particular, EPA determined that the 3 in 10,000 risk level provided "an ample margin of safety, considering the cost, scientific uncertainty, and technological feasibility of control technologies needed to further reduce the radon emissions from [the PG] stacks."[3] EPA may approve new uses of phosphogypsum that are demonstrated to be protective of public health with an estimated total risk to any individual of no more than 3 in 10,000.

---

[1] USEPA PG Workbook, supra note 4, at 5.

[2] EPA, National Emission Standards for Hazardous Air Pollutants; National Emission Standards for Radon Emissions from Phosphogypsum, 57 Fed. Reg. 23,305, 23,311-12, 23,316 (1992).

[3] USEPA PG Workbook, supra note 4 at 5.

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Consistent with standards for radiological protection, this refers to cancer mortality as a clear endpoint of exposure. For the risk analysis described in this report, dose to risk conversion is expressed in terms of risk per milli Roentgen equivalent man (mrem) of 5 x 10^{-7} (i.e., a risk of 5 in 10,000,000 per mrem).

As previously indicated, this risk assessment describes the potential uses of PG in road construction and lays out the potential associated exposure pathways and estimates the risk for workers and members of the public who work in the construction of roads, who live proximate to roads constructed from PG, and who use the roads once constructed (referred to as receptors). The following receptors were considered and assessed with the results demonstrating that the receptors have reasonable maximum exposures (RME).

- Road Construction Worker who works on roads built exclusively with PG material for 5 years;
- Road User (motorist/bicyclist) on PG-constructed roads for 26 years;
- Resident Living Near Road who lives for 26 years 50 feet (ft) from a road;
- Truck Driver who delivers PG for road base material to construction site for 5 years;
- Utility Worker trenching across PG-containing road base for up to 160 hours in a year.

The annual doses to a reasonably maximally exposed receptor for each of the above scenarios was estimated for both annual exposure and for the assumed exposure duration.

The total doses estimated for each of the road exposure scenarios described earlier in the report are summarized in the following Table ES-1. The table also summarizes the corresponding risks arising from the duration of exposure assumed for each scenario and receptor.

Table ES-1 Dose and Risk Summary for All Scenarios

Receptor	CSM	Exposure Duration (years)	Exposure Dose (mrem)	Estimated Cancer Risk	Background Dose From Exposure Duration (mrem)	Exposure Dose Percentage of Background Dose (%)
Reasonable Maximum Exposure Scenarios						
Road Construction Worker	PG in Road Base	5	110	0.5 in 10,000	1550	7%
Road User (Motorist/Bicyclist)	PG in Road Base & Surface	26	28	0.1 in 10,000	8060	0.3%
Truck Driver	PG-Containing Material for Road Base	5	93	0.5 in 10,000	1550	6%
Nearby Resident	PG in Road Base & Surface	26	16	0.08 in 10,000	8060	0.2%
Utility Worker	PG in Road Base	1	0.8	0.004 in 10,000	310	0.3%
	EPA Cancer Risk Management Goal		600	3 in 10,000	600	

Estimated cancer risk below this goal.

All of the predicted risks for the RME receptors are below the EPA's risk management safe level for new uses of PG of 3 in 10,000. As explained in the following sections, the average annual dose to anyone in the US is about 310 mrem per year (as per NCRP 160). This value is provided in this table and the subsequent figures as a point of reference.

Figure ES-1 below shows the estimated annual doses for each of the receptors. Figure ES-2 shows the estimated doses for the assumed duration of exposure ("exposure dose") and Figure ES-3 shows the corresponding estimated cancer risks. It is clear from Figure ES-1 that the annual doses estimated for the various receptors arising from the use of PG in road construction are small and indeed, reflect only a small fraction of the unavoidable dose from natural background radiation.

Figure ES-2 below demonstrates that the exposure dose for each scenario is well below the dose of 600 mrem which is equivalent to EPA's cancer risk goal of 3 in 10,000.

Figure ES-3 below shows the estimated cancer risk from use of PG in road construction is well below EPA's reference risk of 3 in 10,000.

Overall, the use of PG in road construction will result in very small doses (to reasonably maximally exposed receptors) and total risks are well below EPA's reference risk goal.

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Figure ES-1 Estimated Annual Doses

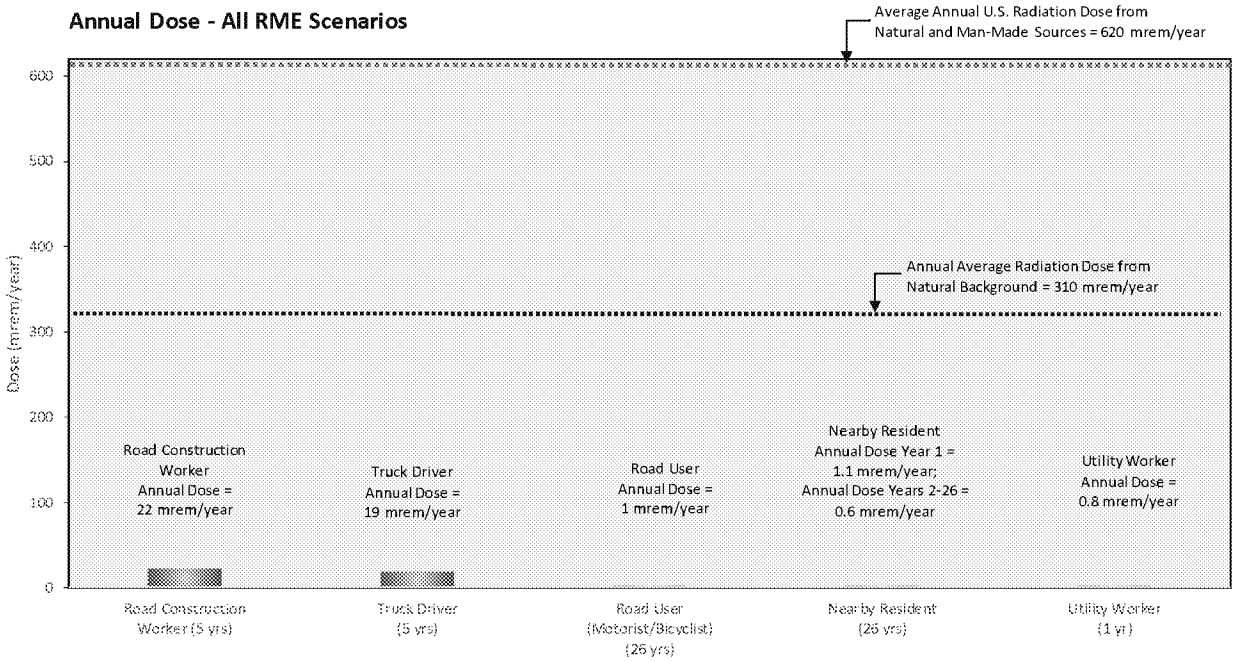

Figure ES-2 Estimated Exposure Doses

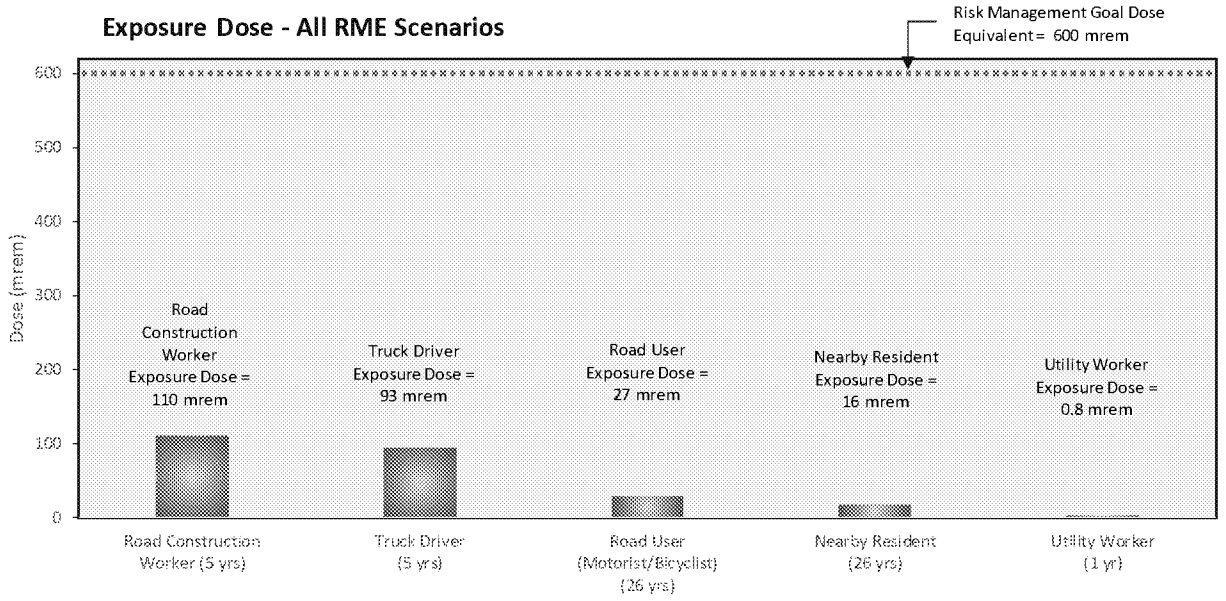

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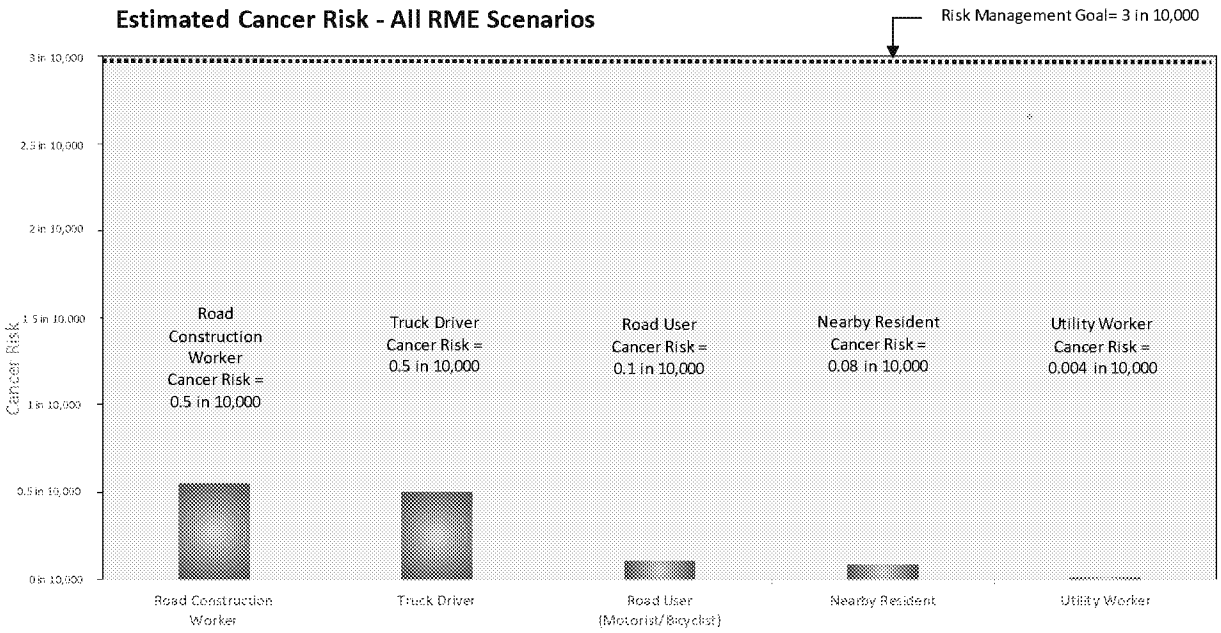
Figure ES-3 Estimated Cancer Risks



[1] The mrem is a common unit of radiation dose. In this report, "dose" refers to effective dose, which simply means that when a person is exposed to a uniform radiation (i.e., external gamma radiation), that all of the doses to the different organs are weighted by their radiosensitivity and added together.

1 INTRODUCTION

1.1 Background

The risk assessment described in this report is provided in support of a petition ("Petition") for EPA approval of the beneficial use of PG. While many potential beneficial uses of PG can, and have been contemplated, the current risk assessment is focused on the potential beneficial uses of PG for the construction of roads.

1.2 Risk Level Criteria

The approach to risk assessment for use of PG in road construction is based on EPA guidance and regulation regarding the appropriate risk benchmark for judging reuse of PG (i.e., specified in EPA's Phosphogypsum Petition Guidance [2005] and EPA's 1992 NESHAP as noted below). In addition, generally accepted national and international procedures for relating radiation dose to risk are considered. This latter consideration includes the rationale for using risk of fatal cancer as the endpoint for radiation exposure.

For present purposes, the guidance provided in EPA's 1992 NESHAP regulation to establish the target lifetime dose and cancer mortality risk for PG reuse is adopted. Specifically, EPA stated (NESHAP, 1992) *"certain uses of phosphogypsum may be considered acceptable so long as those uses are restricted to limit the estimated lifetime risk to any individual to no more than 3 in 10 thousand."* [i.e., a lifetime risk of 3/10,000]. Consistent with standards for radiological protection this refers to cancer mortality as a clear endpoint of exposure. As discussed below, this also is approximate for all calculated detrimental effects.

The International Commission on Radiological Protection (ICRP) sets out the basis for evaluating health effects from radiological exposure along with recommendations for using specific values for regulatory purposes. While there are broad uncertainty bounds at low-dose exposures, the assumption of a linear relationship between exposure and risk is maintained regardless of the possibility of a threshold below which there is no risk. Within this band, ICRP in Publication 103 (2007) has identified specific exposure values for consideration.

ICRP provides analyses for detriment-adjusted cancers that include non-fatal cancers and other types of effects. That calculated value is 5.5% per Sievert. On the basis of model uncertainty and epidemiological evidence[4] the ICRP (2007) offers this judgement given the numerical proximity of the two values (fatal and detriment-adjusted):

> "*It is therefore the recommendation of the Commission that the approximated overall fatal risk coefficient of 5% per Sv* [i.e., 5/10,000,000 per mrem] *on which current international*

[4] Epidemiological information on radiation-associated risks comes from many sources: studies of the survivors of the atomic bombings in Japan; groups exposed in their working environment; patients irradiated in the course of medical procedures; and people exposed to environmental sources of radiation.

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> *radiation safety standards are based continues to be appropriate for the purposes of radiological protection."*

For our risk analysis, we use a dose conversion expressed in terms of millirems or mrem[5]. One Sievert is equivalent to 100 rems or 100,000 mrems. Translating from the 5% risk per Sievert recommended by the ICRP for regulatory purposes, to risk per mrem yields 5×10^{-7} risk per mrem.

The current analysis estimates the annual dose for each of the exposure scenarios, summed over the associated years of exposure to provide a total dose which is then converted to a risk (of fatal cancer) using a dose-to-risk conversion factor of 5×10^{-7} (i.e. 5/10,000,000).

Our use of 5×10^{-7} as a dose to risk conversion as set forth by ICRP is consistent with EPA risk assessment procedures.[6] The EPA (2011) provides cancer risk factors for uniform whole-body exposures of low-dose gamma radiation to the entire population, and reports an estimated 90% confidence interval for cancer mortality of 2.8% to 10% per Gray (Gy)[7] (i.e., from 2.8×10^{-7} to 10×10^{-7} per mrem). This range is essentially the same dose to risk conversion range derived by ICRP.

The value we use is also consistent with the perspective of the National Council on Radiation Protection and Measurements (NCRP) on this matter. The most recent report of the NCRP (2018) (Report No. 180) provides detailed discussion of the risks from exposure to ionizing radiation and states that:

> "*The value of 5 % per Sv* [i.e., 5/10,000,000 per mrem] *is a rounded value for radiation detriment used to inform all the NCRP recommendations regarding stochastic effects.*"

Thus, the risk estimates derived for PG are conservative assumptions based on a linear relationship between dose and risk for the very low dose exposures derived for this report. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2011) notes that below doses of 100 to 200 milligray (mGy) (roughly equivalent to 10,000 to 20,000 mrem): "*epidemiological studies alone are unlikely to be able to identify significant elevations in risk.*" Despite this, we have used EPA's assumption that the risk is proportional to the dose no matter how small the dose. This concept is referred to as linear-no-threshold or LNT.

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[5] The mrem is a common unit of radiation dose. In this report, "dose" refers to effective dose, which simply means that when a person is exposed to a uniform radiation (i.e., external gamma radiation), that all of the doses to the different organs are weighted by their radiosensitivity and added together.

[6] Similarly, the international community has widely adopted the International Atomic Energy Agency (IAEA) determination that 1 millisievert (1 mSv) per year is the acceptable level of radiation exposure (for example, the European Union [EU] regulations). See International Atomic Energy Agency, Radiation Protection and Management of NORM Residues in the Phosphate Industry, Safety Report Series No. 78, IAEA, Vienna, 2013, p. 165. The IAEA and EU determinations are also based on the International Commission on Radiological Protection, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication No. 103, March 2007, p. 55, Table 5 - p. 97, Table 8 - p. 116.

[7] For practical purposes for gamma radiation, 1 Gy = 1 Sv = 100 rem = 100,000 mrem.

The ICRP and NCRP recommended value of 5 x 10^{-4} risk per rem (5 x 10^{-7} per millirem) is used in the Petition and this risk assessment report to convert radiation dose to risk.

1.3 Report Outline

As previously indicated, this risk assessment describes the potential uses of PG in road construction and lays out the potential associate exposure pathways for workers and members of the public who work in the construction of roads, who live proximate to roads constructed from PG, and those who use the roads once constructed. At EPA's request, the ultimate disposition of a PG roadway has also been evaluated. This evaluation was therefore, expanded to include a Reclaimer exposure scenario. It should be noted, however, this reclaimer scenario is not viewed as a reasonable maximum exposure (RME), given the nature and use of planned and constructed public roads.

This risk assessment evaluates the use of PG in road construction, which represents an opportunity for use of PG in support of transportation infrastructure. The following three road construction uses for PG are considered:

1. Road base – PG and soil mixture
2. Road pavement – PG in concrete
3. Road base and pavement – PG in both

Chapter 2: Study Approach. This Chapter describes the scenarios selected for risk assessment, potential receptors and exposure pathways (via use of conceptual site models), the basic models used to perform the risk assessment, and the development of model parameters and the assumptions needed to support the risk assessment.

Chapter 3: Dose and Risk Estimates. Provides the dose and risk estimates, and an evaluation of the ultimate disposition of a PG roadway.

Chapter 4: Discussion. Reviews the risk assessment results and provides a risk context.

Chapter 5: References. Provides the references for materials cited in the risk assessment.

<u>Appendices</u>

Appendix A: Bibliography. Provides an extended list of relevant materials

Appendix B: Excel Workbook with Exposure Parameters

Appendix C: RESRAD Output

Appendix D: MicroShield® Output

2 STUDY APPROACH

This Chapter provides a description of the exposure scenarios for each of the possible uses of PG in road construction. In addition, the models, key assumptions and model parameters used in the analysis are described. Further information on the assumptions and model parameters is presented in Appendix B of this report.

2.1 Conceptual Exposure Model

The focus of this petition is on the use of PG in road construction. The use of PG was considered in the road base and in paving mixed with cement for the concrete surface. A conceptual exposure model was developed for the following uses:

- PG in road base during construction with no surface material present.
- PG in road base (mixed with soil and compacted) and PG in the concrete paving on the road surface.
- Road base without PG and PG in the concrete paving on the road surface.

The selected example road was a four-lane county road with two lanes in each direction. This type of road is common in rural, suburban and urban settings. Choice of this road type permits evaluation of construction workers, nearby residents, bicyclists and motorists, and utility workers. The road dimensions are 15 m wide (about 12 feet [ft] per lane) and 100 m long (segment length) for modelling exposures. The thickness of the road base containing PG and road surface (i.e., pavement) are 0.25 m and 0.12 m respectively consistent with the EPA BID (1992). Exposure scenarios include construction periods and post-construction. Each exposure scenario is defined in terms of nature of activity, proximity, and duration.

2.1.1 Receptors and Potentially Complete Exposure Pathways

Five exposure scenarios were defined, including receptors who would reasonably be expected to receive a dose either during or after construction (Table 2.1). These receptors include the truck driver hauling PG to the road construction site or the concrete production facility, the construction worker building the road, the resident living near the road both during and after construction and the road user, including a driver and bicyclist. In addition, a worker who spends time working on a buried utility in a trench cutting through the road and road base was assessed.

A variety of potential exposure pathways were reviewed and those potentially resulting in a non-negligible dose were selected[8]. These included direct radiological exposure from the volumes of material with PG, and ingestion and inhalation of fugitive dust. Table 2.1 presents the receptors, exposure pathways,

[8] Various authors have reviewed the potential doses arising from the use of PG in road construction, among them, the EPA in their BID (EPA 1992). Exposure pathways other than those discussed in this report were shown by EPA to have doses and risks an order of magnitude or more below those discussed in this report.

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emission source, and type of exposure. Figure 2.1 shows graphical depictions of these exposure scenarios. No other pathway was determined as viable or would result in a non-negligible dose.

Table 2.1 Exposures, Receptors and Complete Exposure Pathways

Exposure Scenario	Exposure	Exposure Pathway
Truck driver-PG to construction site)	Gamma radiation	Direct external exposure
Road Construction Worker	Gamma radiation & PG dust	Direct external exposure Inhalation /Incidental ingestion of dust
Utility worker	Gamma radiation & PG dust	Direct external exposure Inhalation /Incidental ingestion of dust
Road User (bicycle or auto)	Gamma radiation	Direct external exposure
Nearest Resident	Gamma radiation & PG dust	Direct external exposure Inhalation /Incidental ingestion of dust

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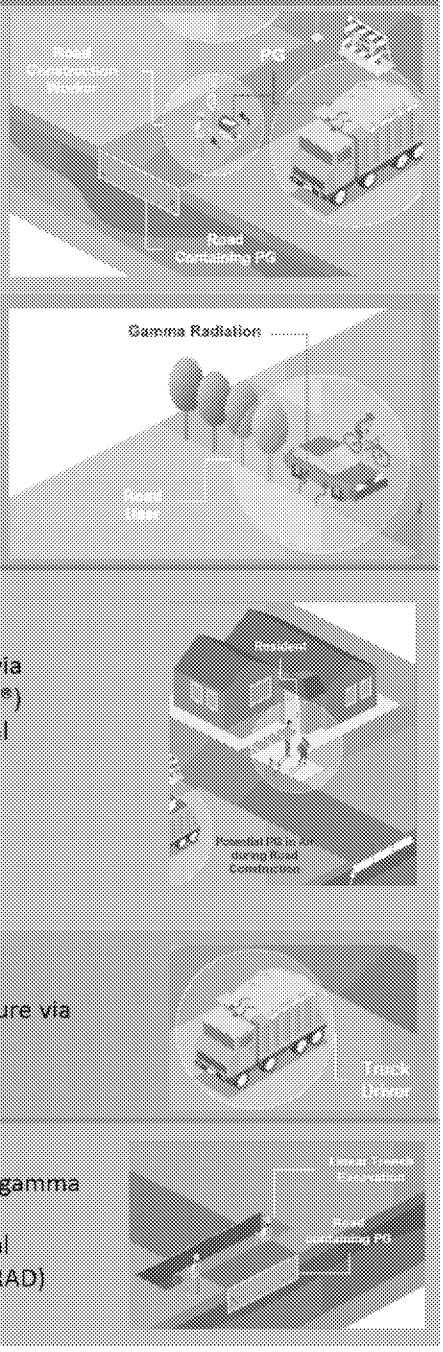
Figure 2.1 Graphical Representation of Complete Exposure Pathways

Receptor	Conceptual Site Model
Road Construction Worker	▪ PG in road base: Exposure via external gamma, inhalation, incidental ingestion (RESRAD)
Road User (motorist/ bicyclist)	▪ PG in road base and paving: Exposure via external gamma (RESRAD)
Resident Living Near Road	▪ PG in road base and paving: Exposure via external gamma (all years) (MicroShield®) ▪ PG in road base: Exposure via incidental ingestion and inhalation during construction (35 days) (RESRAD)
Truck Driver	▪ PG road base material in transit: Exposure via external gamma (MicroShield®)
Utility Worker	▪ PG in road base: Exposure via external gamma (MicroShield®) ▪ PG in road base: Exposure via incidental ingestion and inhalation modeled (RESRAD)



2.2 Source Term

The source term used in the dose calculations and risk assessment is the average radium-226 measured in various PG stacks in Central Florida conducted by EPA in 1988 (EPA, 1988). The measured isotopes were Ra-226, U-234, U-238, Th-230. Po-210 and Pb-210 (dry weight). These radionuclides were assumed to be in secular equilibrium. For the source term, the primary radionuclide is Ra-226 and its daughters. The Th-232 chain was ignored as the concentration of Th-232 in PG was shown to be less than 1 picocuries per gram (pCi/g) (EPA, 1988) which would not result in a measurable incremental dose.

It is also noted that the activity of U-238, U-235 and Th-230 is relatively low: U-238 and U-234 activity of 3.2 pCi/g and Th-230 activity of 5 pCi/g. These isotopes were included although the dose is also negligible since they are not gamma emitters and at best may contribute to small increment of ingestion or inhalation dose. Table 2.2 presents the PG source terms.

Table 2.2 PG Source Terms

Radionuclide Concentrations				
PG Concentration (Source)				
Radionuclide	Concentration (pCi/g)			Comments
U-238	2.9	±	0.5	EPA 1988 Page 4-12
Th-234	2.9	±	0.5	Equilibrium with U-238
Pa-234m	2.9	±	0.5	Equilibrium with U-238
U-234	3.2	±	0.5	EPA 1988 Page 4-12
Th-230	5	±	0.4	EPA 1988 Page 4-12
Ra-226	27	±	0.4	
Rn-222	27	±	0.4	Equilibrium with Ra-226
Po-218	27	±	0.4	Equilibrium with Ra-226
Pb-214	27	±	0.4	Equilibrium with Ra-226
Bi-214	27	±	0.4	Equilibrium with Ra-226
Po-214	27	±	0.4	Equilibrium with Ra-226
Pb-210	27	±	5.4	Equilibrium with Ra-226
Bi-210	27	±	5.4	Equilibrium with Pb-210
Po-210	27	±	5.4	Equilibrium with Ra-226

Notes:
1 Calculated from average 2σ uncertainty (percent)
2 The following activity ratios from EPA 1988 Page 4-12, Table 4-7 were used:
Ra-226 / U-238 = 9.2
Th-230 / U-238 = 1.7
U-234 / U-238 = 1.1
3 Th-234 and Pa-234m were assumed to be in equilibrium with U-238 and the remaining progeny were assumed to be in equilibrium with Ra-226.

The level of radium-226 within PG stacks varies. To address this, we have assumed for purpose of illustration, an empirical average concentration of 27 pCi. Ra-226 in PG (USEPA 1988). Recent measurements of radioactivity (notably Ra-226) in multiple PG stacks confirm the applicability of the forgoing radionuclide source term. However, as discussed later in Chapter 5 of this report, the doses and consequent risks can be scaled on the basis of the Ra-226 concentration by ratioing the average Ra-226 concentration in PG proposed for use in road construction to the doses and risks calculated assuming 27 pCi/g.

Road base is presumed to be up to a 50/50 mixture of PG and soil[9]. This reduces the source concentration by ½ relative to the raw PG source (Table 2.3). The concentration of radionuclides in concrete paving is assumed to be 2.25% PG, based on PG 15% by weight in cement and cement 15% by weight in concrete resulting in proportional reductions in concentrations (Table 2.4).

Table 2.3 Radionuclide Concentrations in Road Base

Radionuclide	Concentration (pCi/g)	Concentration (pCi/cc)
U-238	1.5	3.3
Th-234	1.5	3.3
Pa-234m	1.5	3.3
U-234	1.6	3.6
Th-230	2.5	5.6
Ra-226	13.5	30.4
Rn-222	**13.5**	**30.4**
Po-218	13.5	30.4
Pb-214	13.5	30.4
Bi-214	13.5	30.4
Po-214	13.5	30.4
Pb-210	13.5	30.4
Bi-210	13.5	30.4
Po-210	13.5	30.4

pCi/cc = picocuries per cubic centimeter

[9] A 50:50 mixture of PG and local construction materials such as sand is likely to be an overestimate of the actual mix. The EPA for example in their 1992 BID use a1:2 mix of PG:sand. This is also the ratio in the Polk and Columbia county roads constructed by FIPR with input on the design and testing of the roads from the University of Miami and the Bureau of Materials & Research, the Florida Department of Transportation. The ratio of PG:soil, the use of additives such as cement and thickness of road base for example, will vary depending on the specifications provided by the appropriate authority (i.e., local, state or national Transportation departments). Further, The U.S. Federal Highway Administration (FHWA) Use Guidelines for Waste and By-product Materials in Pavement Construction at 4-17 (1998) (available at https://rosap.ntl.bts.gov/view/dot/38365) which suggests that the limits of blending recycle material in pavement materials ranges from 50% or less for boiler slag to about 55 for fly ash.

Table 2.4 Radionuclide Concentrations in Road Surface

Radionuclide	Concentration	Concentration
	(pCi/g)	(pCi/cc)
U-238	0.066	0.1
Th-234	0.066	0.1
Pa-234m	0.066	0.1
U-234	0.073	0.1
Th-230	0.11	0.2
Ra-226	0.61	1.215
Rn-222	0.61	1.215
Po-218	0.61	1.215
Pb-214	0.61	1.215
Bi-214	0.61	1.215
Po-214	0.61	1.215
Pb-210	0.61	1.215
Bi-210	0.61	1.215
Po-210	0.61	1.215

Notes:

1 The following activity ratios from EPA 1988 Page 4-12, Table 4-7 were used:
Ra-226 / U-238 = 9.2
Th-230 / U-238 = 1.7
U-234 / U-238 = 1.1

2 Th-234 and Pa-234m were assumed to be in equilibrium with U-238 and the remaining progeny were assumed to be in equilibrium with Ra-226.

2.3 Models Used in Risk Assessment

The selected exposure computer codes (models) used to determine the dose for the various exposure pathways were RESRAD and MicroShield®. These codes are used throughout the industry for dose assessments, risk assessment (RESRAD) and gamma exposure and shielding determination for simple configurations (MicroShield®). These codes have been used by EPA, DOE, and DOD extensively for a variety of situations where NORM has resulted in doses to the public or workers. Each of these Codes have benefits and limitations and are used here for appropriate specific configurations. These codes are described in more detail in the next sections. In addition, where required, spread sheet calculations using Excel were used and as appropriate, described later in this report.

It is noted that these codes have replaced those used previously by EPA to evaluate doses and risks in their 1982 Basic Information Document – Potential Uses of Phosphogypsum and Associated Risk (EPA May 1992). The codes used at the time were the PATHRAE code (aka PATHRAE_EPA) and MicroShield®. The latter, MicroShield, was used to augment the results of the PATHRAE analysis. The PATHRAE dose assessment model was published in 1987 (EPA 1987) and while still available, is not currently used.

2.3.1 RESRAD

RESRAD Onsite (RESRAD) is one of a series of codes designed by Argonne National Laboratories for the Department of Energy for the purpose of estimating doses to an individual located on top of radioactively contaminated soils (http://resrad.evs.anl.gov/ accessed 9 12 2019).

Dose calculations are scenario driven using nine exposure pathways. This risk assessment for PG used in road construction includes the following three applicable pathways: (1) direct external radiation from radionuclides in soil, (2) inhalation of airborne radionuclides resuspended or volatilizing from soil, and (3) incidental ingestion of soil. Input information needed for the calculation includes characteristics of the PG material, and properties of surface soil and exposure pattern strata.

For the external radiation dose, the dose is first calculated for an individual exposed continuously to radiation from an infinite depth and lateral extent. The dose point is at a distance of 1 m from the ground surface. Four adjustment factors are applied which are:

- Occupancy and shielding factor – fraction of time indoors and the reduction in the gamma exposure from the structure
- Depth and cover factor – adjustment for source thickness and depth

The default RESRAD model parameters are further discussed in Appendix A of the RESRAD User Manual. While useful for many exposure scenarios, RESRAD cannot calculate doses from complex geometry or shielding other than a finite slab of varying thicknesses and shapes. Also, doses at dose points other than at one meter above the ground surface cannot be calculated.

2.3.2 MicroShield®

MicroShield® is a commercially available gamma ray dose assessment and shielding code (Grove Software https://www.radiationsoftware.com/) that is widely used in determining gamma ray doses, designing radiation shields, estimating source strength from radiation measurements and minimizing exposure. It uses a point-kernel method for exposure rate calculations and, as such, reduces the computational burden which is inherent in Monte Carlo codes such as MCNP the Monte Carlo N-Particle Transport Code.

In the point kernel method, the radiation source is cut up into elementary cells (point kernels). Each point kernel is transmitted through a material using deterministic methods (i.e. attenuation coefficients, buildup factors etc.) which are typically based on the energy of the gamma ray kernel. Each kernel gives a contribution to the dose at the selected dose point (HPS Chabot reference). MicroShield® is capable of using sixteen different source geometries: 1) Point, 2) Line, 3) Disk, 4) Rectangular Area - Vertical, 5) Rectangular Area - Horizontal, 6) Sphere, 7) Cylinder Volume - Side Shields, 8) Cylinder Volume - End Shields, 9) Cylinder Surface - Internal Dose Point, 10) Cylinder Surface - External Dose Point, 11) Annular Cylinder - Internal Dose Point, 12) Annular Cylinder - External Dose Point, 13) Rectangular Volume, 14) Truncated Cone, 15) Infinite Plane, and 16) Infinite Slab.

For the current risk assessment, the rectangular volume best reflects the use of PG in a road base. Shields can be used on the source geometries such as a shield between a truck driver and the carried load of PG (i.e., the driver is shielded by the steel in the truck box).

MicroShield® also contains a wide variety of custom source and shield material. In addition, the code allows for input of different source and shield materials with different densities and atomic weight percentages which provide for the calculation of attenuation and build-up factors. For example, phosphogypsum is a source material in the truck box for the truck driver scenario.

While having broad applicability, there are nonetheless limitations to the use of MicroShield®. The principle limitation is that it is not an exposure pathway code; only doses from direct gamma exposure can be calculated. It was not designed to evaluate ingestion, inhalation, radon or other pathways. It also has limitations on the geometric/shielding configurations which it can accept. For example, while MicroShield® can calculate doses at off road locations in the case of a nearest resident, it cannot calculate the effects of a cap on the road surface at nearest resident dose point locations off the road. These were estimated using other methods.

2.3.3 Spreadsheet Calculations

While the reclaimer scenario is not considered a reasonable maximum exposure (RME) scenario, the scenario was included in the current assessment at the request of EPA.

For the reclaimer scenario, a combination of RESRAD and spreadsheet calculations were used. Gamma doses were estimated using RESRAD and a Spreadsheet model was used to derive radon flux estimates using accepted approaches (USNRC Regulatory Guide 3.64). In particular, this approach was used to calculate radon flux into a home built on a decommissioned road.

2.4 Approach to Developing Model Inputs and Parameters

This section presents the parameters used in MicroShield® and/or RESRAD. A detailed parameter list is included in Appendix B.

Model inputs and exposure parameters were developed to portray reasonable maximum exposure (RME) scenarios that are developed from a combination of assumptions such that use of alternative assumptions are more likely than not to result in a lower dose (and risk). The RME scenario considers the highest exposure that might reasonably be expected to occur, one that is well above the average case of exposure but within the range of possibility and is intended to provide the basis for estimating the maximum individual risk (MIR). Use of the RME to model baseline human health risks is a conservative approach, in that it yields upper-bound cancer risk and non-cancer hazard estimates (USEPA, 1989) and as discussed in a later Section of this report, alternative assumptions are more likely than not to result in lower exposures and doses than those calculated for the RME.

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The model parameters used in the current assessment are a combination of default RESRAD parameters (dose conversion factors for example), default EPA RME exposure parameters (soil ingestion rates and resident exposure duration for example) and parameters such as duration of exposure for road construction workers that were developed as reasonable upper bound values.

The road construction worker exposure duration of 5 years is a conceptual timeframe that represents a portion of industry tenure that would be constructing roads with PG. For example, 80% of the 25-year worker tenure recommended by USEPA (2014) is 20 years and 5 years assuming 25% of that time is spent constructing roads with PG. As another example, a 5-year exposure duration equates to 70% of the Florida Department of Transportation's (DOT's) largest project, the "I-4 Ultimate", which was a $2.3 billion, 21 mile stretch of roadway that took 7 years to complete[10]. Additionally, assuming 70% of two Florida DOT projects with the largest schedule over-runs, which average approximately 3 years for 2010-2017[11], the result would be constructing roads with PG equated to approximately 4 years. Actual exposure to PG in road construction is likely less than 5 years.

Exposure duration is a sensitive parameter in considering dose over an entire exposure period, thus, also in considering cancer risk. Table B.2 in Appendix B summarizes the evaluation of exposure duration for a number of the RME receptors, including a comparison between previous work, various guidance, and values used in this assessment.

As noted above, the hypothetical reclaimer scenario is not considered to be a reasonable maximum exposure (RME) scenario but is nonetheless discussed in a later Section (Section 3.4) for completeness.

2.4.1 Baseline Parameters for Microshield

The following parameter values were used in the MicroShield® calculations:

Densities/Composition

- Source density - The source density was 2.25 g/cc which is standard for concrete.
- Phosphogypsum density - the density of phosphogypsum was 1.12 g/cc (EPA, 1988).
- Air – the density of air 0.00122 g/cc (MicroShield® handbook).
- Concrete composition – The atomic composition and weight percent were from MicroShield® standard (MicroShield® User's manual).
- Phosphogypsum composition - The atomic composition and weight percent were taken from (EPA, 1988).

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[10] Florida DOT "I-4 Ultimate": https://i4ultimate.com/project-info/ and https://i4ultimate.com/documents/2014/09/2014-09-05-I-4-Ultimate-Fact%20Sheet.pdf.

[11] Florida Transportation Commission Performance and Production Review Reports, FY2010-2011 through FY2016-2017: http://www.ftc.state.fl.us/reports/pandpreview.shtm. Preliminary calculations for a subset of projects, excluding projects that appear to involve other primary activities such as railway and signal work.

- Soil Composition – The atomic composition and weight percent were taken from Federal Guidance Report 13 (EPA, 1999).

Other Input Parameters

Build-up – The source material was selected as the build-up material as that is assumed to provide the greatest dose for the receptor locations.

Integration Parameters – As noted in a point kernel code the dose is the sum of numeric integration of each kernel dose over the X, Y and Z direction. These need to be selected in MicroShield® to assure the calculated dose converges to a fixed value. Normally these were set to X=20, Y=40, Z=40 but vary with the scenario.

Radionuclides

Source term included radium and all the daughters in secular equilibrium. The radium concentration was 13.5 pCi/g (Ra-226). It was converted to pCi/cc and increased by a factor of ten half-lives and input into MicroShield®. The decay function in MicroShield® was then used to decay the source by ten half-lives which generated all the daughters including the branching ratios.

It is also noted that PG has some minor activity of U-238 through Th-230, the initial portion of the U-238 decay chain. The activity was a few pCi/g (2 to 3 pCi/g). These radionuclides were not considered further in all the dose calculations because the addition dose from this group was shown to be less than about 0.1%.

2.4.2 Baseline Parameters for RESRAD

The following parameter values were used in the RESRAD calculations:

Densities/Composition

- Density of compacted road base and concrete paving - The density of 2.25 g/cc, standard for concrete, was used for road base and road surface for all scenarios, and for soil cover and concrete foundation density for the reclaimer scenario.
- Road area – 1,500 square meters (m^2), 15 m wide by 100 m in length, as described previously in Section 2.1.
- Road base and road surface thickness – 0.25 m and 0.12m, respectively, as previously describe in Section 2.1.

Exposure and Transport Parameters

- Soil ingestion rates – A soil ingestion rate of 82.5 grams per year (g/year) was used for road construction workers and utility workers and 36.5 g/year was used for road users and nearby

resident receptors. These values are consistent with current EPA defaults within the Superfund Program for workers (i.e., 330 milligrams per day [mg/day]) and residents (i.e., 100 mg/day) (EPA, 2014).

- Outdoor time fractions – the following outdoor time fractions were assumed, based on the time each receptor is at the road construction site, on the completed road, or living near the completed road:
  - Road construction worker – 2,000 working hours per year. Fraction = 2,000 hrs / (365 days x 24 hours/day) = 0.23
  - Road user – 500 commuting hours per year. Fraction = 500 hrs / (365 days x 24 hours/day) = 0.06
  - Nearby resident and reclaimer resident – RESRAD default (ANL, 2015), Section 9.6, page 246.
  - Utility worker - 8 hours/day, 5 days/week, for 4 weeks = 160 working hours per year. Fraction = 160 hours / (365 days x 24 hours/day) = 0.018

- Inhalation rates – The RESRAD default inhalation rate of 8,400 cubic meters per year (m^3/yr) was used for the nearby resident receptor. A higher inhalation rate of 11,400 m^3/yr was assumed for road construction workers and utility workers. This value was the RESRAD version 6 default for industrial workers and assumes an hourly rate of 1.3 m^3/hr (EPA 1997).
- Mass loading to air – The mass loading factor of 0.0002 grams per cubic meter) g/m^3 for road construction workers and utility workers was used. This value was described in RESRAD support documentation (ANL, 2015) as the upper end of 98th percentile range for PM2.5 concentrations in ambient air. For the nearby resident receptor, a mass loading factor of 0.0001 g/m^3 was used, which is consistent with the EPA BID value of 100 micrograms per cubic meter (µg/m^3).
- Indoor dust infiltration factor – A RESRAD default value of 0.04 was used.

Other Input Parameters

Cover depth – No cover was assumed for the road construction worker who was assumed to work on PG amended road base. A cover depth equal to the road surface thickness was used for the road user receptor, accounting for shielding of road base by the road surface of the completed roadway. A cover depth of 0.2 m was used for reclaimer resident, accounting for 4 inches (10 cm) of stone cover and a 4-inch (10 cm) concrete slab for indoor exposure.

Radionuclides

Source term included radium and all the daughters in road base and/or road surface as described previously in Section 2.2.

3 ESTIMATED DOSES

The estimated doses to the various receptors are discussed below. These include receptors considered in the original 1992 BID and additional receptors requested by EPA. The original receptors were: the road construction worker ("construction worker" in the 1992 BID), the nearest resident ("member of the critical population group-CPG" 1992 BID), road user motorist ("person diving on road" 1992 BID) and reclaimer. The last, the reclaimer, while not considered as a reasonable maximum exposure (RME) scenario, for this work has been assessed as described in Section 3.4.

Based on discussions with EPA additional receptors were requested to be considered. These included a utility worker working in the PG mix portion of the road, the truck driver delivering the PG to the road construction site, and a bicyclist.

The following Table 3.1 provides a summary of the estimated doses for each scenario. As seen from the Table, all the doses are well below the reference dose (cancer risk management goal) of 600 mrem (the dose equivalent of a total risk criteria of 3 in 10,000.

Table 3.1 Dose and Risk Summary for RME Scenarios

Receptor	CSM	Annual Dose (mrem/year)	Exposure Duration (years)	Exposure Dose (mrem)	Estimated Cancer Risk
Reasonable Maximum Exposure Scenarios					
Road Construction Worker	PG in Road Base	22	5	110	0.5 in 10,000
Road User (Motorist/Bicyclist)	PG in Road Base & Surface	1	26	28	0.1 in 10,000
Truck Driver	PG-Containing Material for Road Base	18.6	5	93	0.5 in 10,000
Nearby Resident[1]	PG in Road Base & Surface	--	26	16	0.08 in 10,000
Utility Worker	PG in Road Base	0.8	1	0.8	0.004 in 10,000
		EPA Cancer Risk Management Goal		600	3 in 10,000

All estimated cancer risks below this goal.

[1] *Nearby Resident Annual Dose Year 1 = 1.1 mrem/year; Annual Dose Years 2-26 = 0.6 mrem/year*

The basis for the dose calculations is described in the following Sections.

3.1 Road Construction

3.1.1 Road Construction Worker

This scenario assumes a road construction worker works directly on the surface of the road as it is being constructed, 2,000 hours/year for 5 years. Although some road construction workers are on equipment during the workday which would provide shielding from external gamma exposure, shielding has not been included in the calculations. This approach provides additional conservatism in the estimates of dose to the RME road construction worker. Doses are calculated from the conceptual site models using the computer code RESRAD. The doses are from direct exposure from gamma emission from PG, and inhalation and ingestion from potential dust emission during construction. In all three CSMs the active road

area is 100 m long by 15 m wide, while thicknesses vary with the CSM. As the model used was RESRAD, the exposure point is at one meter above the surface, the RESRAD default. In addition, it was assumed the road construction worker moves around the surface of the road and the direct dose was calculated as the average of the dose at the road center and at the edge of the road. The calculated annual doses from all exposure routes are as follows:

- PG in road base (no cover) – 22 mrem/year.
- PG in road base and in concrete paving – 4 mrem/year.
- Road base without PG and PG in the concrete paving – 0.8 mrem/year.

The first shows the most conservative dose is associated with PG in the road base with no pavement cover. This is the most conservative scenario as road construction workers would spend a portion of time on paved roadway. For the case with PG in the pavement on the road base, the pavement acts as a shield reducing the surface dose. While the PG in the pavement provides a small contribution to the surface dose, the isotopic concentration is much lower, as is the thickness.

Assuming the road construction worker is exposed on the road base with no cover for a period of 5 years, the total dose is 110 mrem or a risk of 0.5 in 10,000.

3.2 Living Proximate

3.2.1 Resident Living Near Road

This scenario assumes a resident lives close to the site of the road as it is being constructed and after construction. In the first case, no shielding (road shoulders, etc.) was assumed during construction. After construction, a shoulder was established. During construction MicroShield® was used to determine the doses at various distances from the road. A rectangular volume was assumed, 15 m wide, 100 m long and 0.25 m thick. The contribution to the receptor is from the side face during construction and the surface of the road following construction. That is the contribution from the side of the road – the 25 cm thickness 100-meter long face and the contribution from the 15 meter by 100 meter surface of the road. Doses were determined at 20 ft and 50 ft from the edge of the road at a receptor height of 1 meter above the road surface. The distance of 20 ft is considered representative of urban settings with houses at a minimum separation from the road edge (urban setting may also have more shielding). The distance of 50 ft is representative of more suburban setting where separation distances between roads and homes are expected to be greater. The calculated dose rates were:

- At 20 ft – 1.14 micro Roentgen per hour (μR/hr) (and where 1 μR = 0.001 mrem, 1.14 x 10^{-3} mrem/hr)
- 50 ft - 0.32 μR/hr (0.32 x 10^{-3} mrem/hr).

These dose rates, calculated as described below, are quite low compared to background and are conservative.

This is expected as for the side face, only the initial two ft (60 cm) of road will contribute gamma radiation. Gammas originating deeper than 50 to 60 cm into the road will be shielded by the road material. For the dose from the surface face, the pathways (allowable angles) to the receptor decrease as the distance from the road edge increases. This field of view of the road surface will continue to decrease the further away a receptor is from the road edge. At a sufficient distance from the receptor the road appears as a line source.

After construction, shielding of the PG amended road base is provided by the fill in the road shoulders and the concrete paving.

Some inherent limitations with the MicroShield® code prevent the geometry of the shielding for this configuration to be calculated directly. Specifically, the shield and receptor heights must be the same, which is not the case here with a 25 cm shield and 100 cm receptor. However, estimates of the reduction in dose were determined. For the dose from the 25 cm edge of the road, a six-foot (2-meter) soil "road shoulder" was assumed and calculated using MicroShield®. This reduced the dose from this face by six orders of magnitude – essentially zero dose. The second face contributing to the dose is the road surface. The dose from the top face of the road is reduced by the concrete paving. A five- to six-inch (13 to 15 cm) concrete shield will reduce the surface dose by a factor if 3 to 4 (Schiager, 1974). Assuming linearity, the estimated dose using a reduction factor of 3.5 following construction of shoulder and placement of road surface over road base, the estimated gamma dose rates at the prior distances are:

- 20 ft – 0.33 μR/hr (0.33×10^{-3} mrem/hr)
- 50 ft - 0.1 μR /hr (0.1×10^{-3} mrem/hr).

The level of residential exposure to radiation from PG used in road construction depends upon whether the PG road base is unshielded and the distance from the edge of the road to nearest RME residence. In all residential scenarios (urban and other locations), we assumed the PG road base is not paved during the first 35 days of construction; therefore, the exposure is higher during this brief period than after the road is completed.

The evaluation assessed urban roads using an RME distance to the nearest residence of 20 ft. But in urban locations, there is more shielding provided by sidewalks and other urban infrastructure; therefore, residential exposure is likely to be lower than the simple estimate.

For roads in non-urban settings, this Report calculates exposure for receptors at both 20 ft and 50 ft from the edge of the road. For this analysis, we used professional judgment to establish an RME distance at 50 ft from the road to the non-urban residence. We also calculated exposure using a distance of 20 ft, to illustrate the degree to which radiation levels decrease with distance.

Exposures of nearby urban, suburban, and rural residences to radiation associated with PG use in roads are reduced not only by the shielding afforded by the road itself but also as a result of distance from the source. At a distance of 20 ft from the completed road, the radiation is already a small fraction of background levels and compared to levels of naturally-occurring radiation would be indistinguishable from natural

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variability of naturally-occurring radiation. This already low level of gamma exposure decreases by an additional 70% between 20 and 50 ft and continues to rapidly decline with distance from the road. Therefore, the exposures considered at 20 ft and 50 ft from the road represent reasonable maximum exposures for residences; residences located further away from a road constructed using PG would be much lower and again indistinguishable from the variability in naturally occurring background.

An estimate of the gamma external dose for the above is as follows. Residence time per year in the residence is 350 days/year (EPA,1991 OWSER 9285). Road construction is expected to be 5 weeks exposing the resident to a road with no shield (pavement) for 35 days (840 hours). The dose at different distances from the road is dose rate times the construction period. The additional dose for the remainder of the year (315 days) uses the shielded dose rate. The total residence time is 26 years or an additional 25 years residence. The total dose during this period ranges from 73 mrem for the closest resident, 20 ft from the road edge to 20 mrem at 50 ft. The average annual dose from natural background is about 310 mrem per year, inclusive of radon. The average annual dose from external gamma is about 82 mrem per year (for further context discussion, see Section 5. Table 3.2 presents the calculation details for all the distances.

Table 3.2 Calculation Details for all Distances

Distance from Road	Dose During Construction in Year 1*		Dose After Construction in Year 1*		Dose After Construction in Years 2 - 26*			
	Rate	Dose	Rate	Dose	Rate	Dose	Total Dose	% gamma background
feet	μR/hr	mrem	μR/hr	mrem	μR/hr	mrem	mrem	%
20	1.14	0.96	0.33	2.5	0.33	69.3	72.8	3.4
50	0.32	0.27	0.1	0.70	0.1	19	20.0	0.9

*For dose during construction - Multiply rate by 840 hours.
*For dose after construction in Year 1 – Multiply rate by 7560 hours.
*For dose for Year 2 to 26 – Multiply by 210,000 hours.
*Divide by 1,000 to convert μR to mrem.

The above results are further reduced by consideration of a "shielding" factor for gamma exposure during time spent inside the house. For present purposes, the RESRAD default shielding factor of 0.7 can be applied for time indoors. Assuming that an individual spends about 70% of his or her time indoors and 30% of his/her time out of doors, then the dose rates and resulting doses are shown in Table 3.3.

Table 3.3 Calculation Details for all Distances with Indoor Shielding

Distance from Road	Dose During Construction in Year 1*		Dose After Construction in Year 1*		Dose After Construction in Years 2 - 26*			
	Rate	Dose	Rate	Dose	Rate	Dose	Total Dose	% gamma background
feet	μR/hr	mrem	μR/hr	mrem	μR/hr	mrem	mrem	%
20	0.90	0.76	0.26	1.98	0.26	54.7	57.5	2.7%
50	0.25	0.21	0.08	0.55	0.08	15.0	15.8	0.7%

*For dose during construction - Multiply rate by 840 hours.
*For dose after construction in Year 1 – Multiply rate by 7560 hours.
*For dose for Year 2 to 26 – Multiply by 210,000 hours.
*Divide by 1,000 to convert μR to mrem.

Calculated doses for incidental ingestion and inhalation during construction are 0.28 mrem and 0.01 mrem, respectively. The annual dose for the first year including 35 days of construction and all exposure pathways of a resident 50 ft from the road is about 1.1 mrem/yr. In subsequent years after construction the annual dose is 0.60 mrem/yr. Assuming the resident is exposed for a period of 26 years, the total dose is 16.1 mrem or a risk of 0.08 in 10,000.

Exposure to children was considered in the risk assessment. Exposure parameters such as ingestion rate and inhalation rate for children are generally higher per unit body mass than for adults; however, childhood is of a shorter duration than adulthood. The dose coefficients for ingestion and inhalation that were used in RESRAD from ICRP 72 vary by about two times; however, dose coefficients for external radiation that were used in RESRAD from ICRP 60 do not vary any age group. Since the bulk of the dose is from external radiation and the portion of the exposure duration as a child is a relatively short, the amount of possible increase in ingestion and inhalation dose for exposure during childhood is small and nominal to the total annual dose. Overall, including the doses received as a child do not have a material effect on the dose assessment and associated risks.

3.3 Road Users

3.3.1 Road Users – Motorist/Bicyclist

Two road users were considered for this scenario, a driver and a bicyclist. In both instances they were assumed to travel on a final constructed road with PG in the road base and the paving. The dose to either road user was calculated as 1.1 mrem/yr. No reduction was provided to the driver as the floor and auto body shielding are assumed negligible given the current materials used thin plastic/metal. Conservatively assuming these road users commute on the road for a period of 26 years, the total dose is 28 mrem or a risk of 0.1 in 10,000.

3.3.2 Utility Worker

The utility worker dose was calculated using MicroShield®. It was assumed that a trench was cut across the road. The utility worker was assumed to work in the middle of the trench about one meter from the face of the road. The dose point was 7.5 m from the road edge, 51 m from the road end and 0.25 m high. The isotopes in the PG were Ra-226 in secular equilibrium with the daughters. The activity was taken as 13.5 pCi/g as the PG was mixed with road surface material at a 1:1 ratio. The calculated hourly dose was 2.08 µR/hr. This was doubled to take into account the other half of the road giving a dose or 4.2 µR/hr. The MicroShield® output in Appendix D.

The direct exposure dose to the utility worker was calculated assuming the utility worker spends 160 hours per year in the PG road. Multiplying the hours worked by 0.0042 mrem/hr results in an external annual dose of 0.67 mrem/yr.

The ingestion and inhalation doses (0.15 mrem/yr and 0.01 mrem/yr) were calculated from RESRAD and was assumed the same as the road construction worker reduced by the hours worked in the trench. The total dose was then estimated by adding external dose which leads to an annual dose of 0.8 mrem/yr. Assuming the utility worker is exposed for a period of 1 year, the total dose is also 0.8 mrem or a risk of 0.004 in 10,000.

3.3.3 Truck Driver

Another receptor is the truck driver who transports PG from the PG stack to the site of the road construction. The truck is assumed to be a standard dump truck. The dose to the truck driver was calculated using MicroShield®. The geometry selected was a rectangular volume, with the dimensions of the roll-off portion being 17 ft long, 4.5 ft high and 7 ft wide which is the average for a 20-ton dump truck. The dose point was one meter from the center of the roll-off front face, where the driver would be sitting. The truck was assumed to be filled with phosphogypsum with a density of 1.12 grams per cubic centimeter ($g/cm^{3)}$ which is somewhat lighter than soil. The isotopes in the PG were Ra-226 in secular equilibrium with the daughters. The activity was assumed 27 pCi/g as the PG was not yet mixed with road surface material. No credit or reduction was taken for the shielding effects of the truck cab. The calculated hourly dose was 19 µR/hr. The MicroShield® output is presented in Appendix D. The annual dose was calculated assuming the driver hauls material for the entire year (2000 hours), however the roll off is only filled half the driving time (1,000 hours). Multiplying the hourly dose by the time hauling PG results in an estimated annual dose of 18.6 mrem/yr. Assuming the truck driver is exposed for a period of 5 years, the total dose is 93 mrem or a risk of 0.5 in 10,000.

3.4 Ultimate Disposition Evaluation

The EPA PG use regulations require an assessment of the risk from the ultimate disposition of PG or any product in which the PG is incorporated. 40 C.F.R. § 61.206. The ultimate disposition of a new road constructed with PG or any product containing PG is considered in terms of what is the reasonable maximum exposure for ultimate disposition.

The RME for ultimate disposition of a new road constructed with PG is that it serves as an established part of municipal (county, state and/or federal) infrastructure and as such would require periodic repair and expansion as needed. These activities could include removing the surface, grinding and reusing or disposing of the materials consistent with federal and state and local regulations. Exposures and risks associated with maintenance of roads and reuse of construction materials are expected to be comparable or less than those detailed in the risk assessment for road construction. It is also noted that as part of road construction, no excess PG is expected to be left over. Road builders avoid transporting extra material to a construction site and would mix in any remaining PG to avoid additional handling.

The sustainability of roads and the reuse of road construction materials are key aspects of guidance and plans for roads under the jurisdictions of the Federal Highway Administration and state Departments of Transportation. The in-place abandonment of municipal infrastructure and allowance for construction of residences on top of these abandoned roads runs counter to sustainable infrastructure projects involving road construction. In any case, the construction activities required for road maintenance result in less exposure than during the original road construction (i.e., the construction activities on scale). Thus, the risk is less than those calculated in this report for the road construction.

3.4.1 Reclaimer Exposure Scenario

At EPA's request, this report includes a reclaimer scenario, which is not considered as a reasonable maximum exposure (RME) scenario. The reclaimer scenario assumes that the home is a bungalow constructed slab on grade with a 4-inch underlying slab and a 4-inch gravel base underlying the slab. The basic scenario takes credit for a vapor barrier but takes no credit for any radon mitigation that might be required for local building codes.

As with the case of the nearby resident, the house is presumed to be occupied for 26 years.

The configuration of the slab on grade construction is for the reclaimer scenario is illustrated in Figure 3.1.

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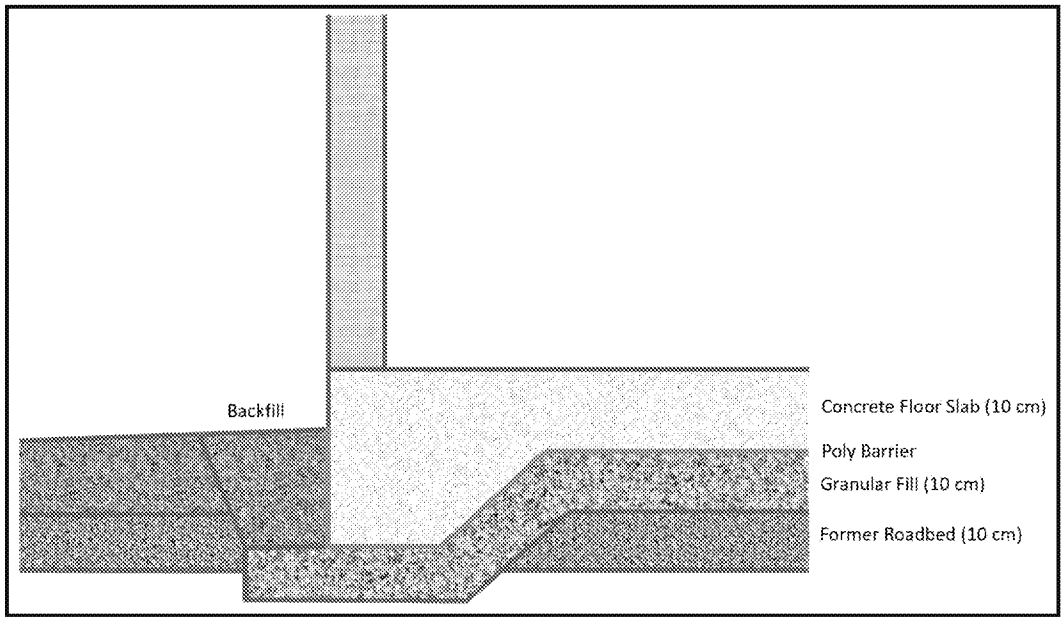
Figure 3.1 Slab on Grade Construction for Reclaimer Scenario



In broad terms, the reclaimer scenario assumes the following:

- Exposure to the reclaimer would be through gamma radiation and the inhalation of Radon (Rn-222) and progeny.
- The reclaimer is assumed to be exposed for 26 years with approximately 75% of his/her time onsite and indoors.

Radon Exposure and Dose

The key assumptions are as follows:

- The road surface has crumbled and has been removed as part of site preparation (50 years after closure also as assumed by the EPA in their 1992 BID).
- Site grading for construction will almost certainly reduce the thickness of the layer containing PG; however, for present purposes, we have assumed that site preparation will reduce the PG layer to about 10 centimeters (cm) in thickness and the concentration of Ra-226 in the remaining layer to about 10 pCi/g.
- Radon flux is reduced due to a 6-millimeter (mm) poly layer as a moisture barrier currently common in building codes. Such a layer would be expected to reduce the radon flux by at least a factor of 10 (Kitto and Perazzo, 2010).

Figure 3.2 illustrates the effect of source thickness on radon flux. Radon flux increases with increasing source thickness up to an approximate thickness of 35 cm. For source thicknesses greater than

approximately 35 cm, radon flux is approximately constant due to the greater diffusion distance and substantive decay that occurs below the surface.

Figure 3.2 shows the calculated radon flux from a bare (uncovered) surface of a PG amended soil layer. The figure assumes a unit concentration of Ra-226 radium in the PG amended surface (i.e., 1 pCi/g). The assumed diffusion coefficient is $4x10^{-4}$ square centimeters per second (cm^2/s) and the emanation E=0.062 (See Rogers *et.al*, 1994 and Chauhan 2015). The radon flux was calculated using the formula in USNRC Reg Guide 3.64. (USNRC 1989).

Thus, the values shown in Figure 3.2 should be multiplied by 10 pCi/g to yield the associated radon flux. For the current assumptions, i.e., 10 cm thick layer of amended PG at 10 pCi/g, radon flux through the surface of a PG amended soil layer 10 cm thick would be about 0.25 pCi/m^2-s. Further, the concrete slab (assumed 10 cm thick) would reduce the radon flux through the slab into the home to about 0.09 pCi/m^2-s. Due to the 6-mm poly vapour barrier will further reduce the radon flux by a factor of 10 (or more). The resulting radon flux into the home is 0.009 pCi/m^2-s.

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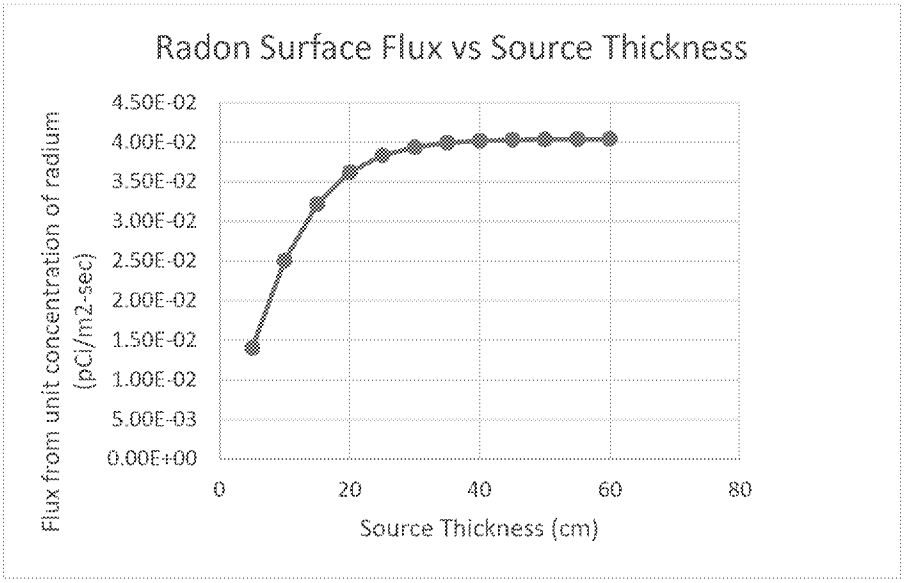
Figure 3.2 Effect of Source Thickness on Radon Surface Flux



The dose from exposure to radon and progeny was estimated using spreadsheets.

As outlined above, the estimated radon flux into the home is about 0.009 pCi/m^2-s. The calculations to convert this flux to a dose are as follows:

Assuming a notional slab on grade house:

A = 100 m^2 (i.e. 10 x 10) } UNSCEAR 2000 Appendix B

V = 250 m^3

S = Source term

= area (m^2) x flux (pCi/m^2.s)

= 100 m^2 x 0.009 pCi/m^2.s

Rn = "radon inventory"

Where s = seconds

Neglecting Rn in outside air and assuming steady state between radon coming into the home and dilution through home ventilation (air changes), we can derive the following equation:

$$Vd\,(CRn)/dt = S - V.C.\ ACH\ (\text{adjustments to s}) - \lambda VC$$

For d(CRn)/dt = 0 the above reduces to

$$C = \frac{S}{V\,(ACH\ (\text{adjustments to s}) + \lambda)}$$

For current assumption:

$$C\ \text{picocuries per liter [pCi/L]} = \frac{100\ m^2 \times 0.009\ \frac{pCi}{m^2.s}}{250\ m^3 \times \left(\frac{1\ hr}{3600\ s/hr} + 2.1 \times 10^{-6}\right) \times \frac{1000\ L}{m^3}}$$

$$\approx 0.013\ pCi/L$$

For context, the National Residential Radon Survey (NRRS) carried out by the U.S. Environmental Protection Agency (EPA) completed in 1991, reports measured radon gas concentrations in U.S. homes at an average of about 46.3 ± 4.4 Becquerel per cubic meter (Bq/m^3) (one standard error) (as cited in NCRP 2019, Report No. 160, Section 3.5.2). Converting from Bq/m^3 to pCi/L, this converts to an average indoor radon level of about 1.25 pCi/L with a one standard deviation at about 0.12 pCi/L. The estimated incremental indoor radon level arising from residual PG under the residence is less than one standard deviation of background. NCRP 160 also indicates that typical outdoor levels of radon are about 15 Bq/m3 or 0.4 pCi/L. Thus, the predicted incremental indoor radon level attributable to PG under the home is small by comparison to either the variation in indoor levels or the typical outdoor level of ambient radon.

Assuming an equilibrium factor of 0.4 and 6000 hours per year of time indoors leads to an exposure of about 0.4 WLM and assuming a 1000 mrem per WLM conversion factor[12] (NCRP 160) this converts to a dose of about 1.8 mrem/year.

Gamma Dose

[12] The conversion factor from WLM to dose has been and continues to be the subject of much discussion. During the initial development of the risk assessment, the use of 400 mrem per WLM was discussed. Upon review, it was decided that the use of 1000 mrem per WLM should be used. The notional value of 1000 mrem per WLM was adopted by NCRP 160. It should be emphasized that most of the risk arising from exposure to radon decay occurs in smokers. See for example discussions in UNSCEAR 2006 Annex E and ICRP reports 115 and 126. In addition, Darby et.al. (2004) indicate that based on a European study of the risks of residential radon, that in the absence of other causes of death, the absolute risks of lung cancer by age 75 years would be about 25 times greater for cigarette smokers than non-smokers. The EPA (2016) provides tables that allow comparison of risks to smokers and non-smokers which show the risk to smokers is a factor of about 10 or so greater than the risk to non-smokers (and former smokers). The lower dose conversion factor might be appropriate for a population of non (or former) smokers.

RESRAD was run for indoor gamma exposure dose for the reclaimer scenario. Indoor exposure (75% onsite and indoors to be consistent with radon assumptions) was modelled for a 100 m^2 source underlying a 10 m by 10 m residence. The 4-inch (10 cm) thick layer of PG amended soil is overlain by a 4-inch layer of cover (10 cm) and a 4-inch (10 cm) thick layer of concrete (floor slab). Neither of these layers are credited for reducing radon flux into the home, but both result in a substantial reduction in gamma levels anticipated on top of the floor slab where people would be exposed.

The gamma dose estimate was performed using RESRAD and for the above assumptions, amount to about 1.2 mrem/y.

Thus, as presented in Table 3.4, for the above assumptions, the dose to a reclaimer is estimated at about 3 mrem/y. Assuming the reclaimer is exposed for a period of 26 years, the total dose is also 78 mrem or a risk of 0.4 in 10,000.

As noted in the discussion of the ultimate disposition scenarios (road abandonment, and the construction of a home on the abandoned road) is not an RME exposure. The fact that this extreme exposure scenario corresponds to a risk below the EPA risk management level confirms that the lesser exposure in the ultimate disposition scenario need not include a numerical risk assessment. (see discuss in section 5 below.)

Table 3.4 Evaluation of Ultimate Disposition of PG Road

Receptor	Exp	Annual Dose [mrem/year]	Exposure Duration [years]	Exposure Dose [mrem]	Estimated Cancer Risk
Hypothetical Scenario Beyond RME for Screening Purposes					
Reclaimer Resident:	PG in Road Base	3	26	78	0.4 in 10,000
		EPA Cancer Risk Management Goal		600	3 in 10,000

Estimated cancer risk below this goal.

3.5 Comparison of Doses and Risks from 1992 BID to Current Estimates

During a meeting with EPA, the EPA indicated that it would be necessary for them to consider how information developed since their 1992 BID might change their risk assessment assumptions. A detailed comparison of models and assumptions used in the 1992 BID and the present report is extremely complex and beyond the scope of the present report. Nonetheless, we have attempted a very "high level" and preliminary overview of the main differences that we could readily identify between the dose and risk results provided in EPA's 1992 BID and those previously discussed in this report.

The EPA in their 1992 BID considered 4 scenarios for use of PG in roads, two which involve use of PG in a secondary road as road base and two which involve use of PG in a concrete road surface:

- For the road base, the EPA assumed a Ra-226 concentration of 30 pCi/g and a 1:2 dilution of PG with soils for a road base concentration of 10 pCi/g. The road base was assumed 0.25 m thick and 30 feet (9.15m) wide and that the road base is covered with a 0.12 m (5 in) thickness of asphalt.
- For use of PG in a concrete road surface, the EPA assumed the road surface incorporates 15% PG by weight and an average Ra-226 concentration of 30 pCi/g (i.e., Ra-226 at 4.5 pCi/g) 0.12 m thick (5 in) and 24 feet wide (7.32 m). The road base under the surface is as described above.

The EPA considered a road construction worker, a person driving on the road (road user) and a nearby receptor (assumed living proximate to the road). The EPA also considered a reclaimer who builds a house on an abandoned road base after the road surface has been removed.

The 1992 BID estimated radiation doses and risks from one year of exposure demonstrated that for practical purposes:

- Dose to a road construction worker is dominated by direct gamma;
- Dose to a road user is only from gamma radiation; and,
- Exposure to the critical population group member (nearby resident 100 m from the edge of the road) is dominated by external gamma radiation.

Calculating the dose and risk from the assumed duration of exposure is done be multiplying the dose or risk from one year of exposure by the number of years a receptor is exposed. As discussed in the 1992 BID, the reclaimer was specified at 70 years of exposure. Clearly, this is an extremely conservative assumption and as discussed elsewhere, this assessment assumes residency of 26 years being the upper end (upper 90th percentile, EPA 2014) of how long someone spends at a particular residence.

The analysis described in the current risk assessment (this report) makes the following key assumptions, a Ra-226 concentration in PG of 27 pCi/g, a 1:1 dilution of PG with soils (higher PG to soil than EPA's 1:2 PG to soil in 1992), and a road thickness of 0.25 m (the same as in 1992). The current risk assessment considers the same receptors as did EPA in 1992 as well as two additional receptors suggested by the EPA, namely, the truck driver transporting PG to the construction site and a utility worker who works some time in a trench cutting across a road constructed with PG.

The following bullet points provide a few additional comparisons between the 1992 BID risk assessment and the current assessment:

- The EPA (at Table 4-16 for a road base of PG and sand) provided results for a variety of Ra-226 concentrations in PG, the highest of which is 26 pCi/g, comparable to our notional assumption of 27 pCi/g.
- The EPA report has four tables of annual doses and associated risks from a single year of exposure:

- For the road construction worker, the EPA considered workers standing on the road base and unshielded as also assumed for the current risk assessment. The current risk assessment assumes a worker moves around over the road surface and is exposed at the average of the gamma fields at the centre and edge of the road. While not fully clear, the EPA in 1992 may have assumed a worker was always in the centre of the road which would largely account in the difference between gamma doses estimated in 1992 and now.
- The road user is assumed in both cases to drive on a road with PG base and a cover (in 1992 asphalt or cement) and in the present analysis, for purpose of illustration concrete road surface was assumed. Only annual dose and risk are available from the 1992 risk assessment. The 1992 EPA risk assessment used a 0.6 shielding for the road user, but rather than determine the degree to which vehicles have changed the amount of metal in the under carriage of cars, the current risk assessment takes no credit for shielding provided by the vehicle which however would provide some level of shielding which is a conservative assumption and could reasonably be considered.
- The dose to the nearby resident is dominated by exposure to gamma radiation which decreases rapidly with increasing distance from the edge of the road. The 1992 risk assessment assumed the nearest resident at 100m (a bit over 300ft) from the edge of the road. The current assessment considers the RME exposure scenario to be a resident whose home is 50 ft from the edge of the road (an urban resident whose home is at 20 ft from the road is also calculated to illustrated the change in exposure levels with distance.
- The current risk assessment considered two receptors beyond those considered in the 1992 BID (truck driver and utility worker).

Both risk assessments considered a reclaimer scenario with exposures from gamma radiation and radon. Both assume the surface is removed. The 1992 analysis assumes the home is built directly on the road base and the current assessment assumes that site preparation and grading take place which reduces the thickness and to a lesser degree, the concentration of residual road base. The 1992 BID does not indicate how the risk from radon was calculated (dose from radon was not reported in the 1992 BID). The 1992 BID assumed 70 years residency and the current assessment assumed a 26-year residency (the upper 90th percentile). The current assessment also assumes a 6 ml poly layer which is standard as a vapor barrier in home construction.

4 RISK DISTRIBUTION DISCUSSION

This risk assessment describes the potential uses of PG in road construction and lays out the potential associated exposure pathways for workers and members of the public who work in the construction of roads or who live proximate to roads constructed from PG and those who use the roads once constructed. As described earlier, the receptor scenarios were selected and designed to have reasonable maximum exposures, doses and risk.

The RME exposure assumptions and parameters were selected to estimate a radiation dose that is consistent with the "reasonable" upper end of the range of plausible exposures. Accordingly, they are generally more likely than not to overestimate the doses and associated risks arising from the proposed alternative use of PG in road construction.

The RME receptors are used to calculate the dose (i.e., the amount of radiation to which the individual in the exposure scenario receives over a particular unit of time). The associated risk is assumed to increase in direct proportion to the dose calculated for the RME (i.e., if the RME increases by a factor of two, the risk increases by a factor of two).

The risks were calculated for each exposure scenario and receptor as follows:

- The dose to the RME is calculated for each year of exposure;
- The total dose is calculated by multiplying the annual dose to the RME by the assumed years of exposure (exposure duration);
- The total radiation dose is converted to risk using a radiation dose to risk conversion factor of 5 in 10,000,000 per mrem;
- The total risk is compared to the EPA's total cancer risk goal for new PG uses of 3 in 10,000 (which is equal to a total dose of 600 mrem).

The total doses estimated for each of the road exposure scenarios described earlier in the report are summarized in the following Table 4.1. The table also summarizes the corresponding risks arising from the duration of exposure assumed for each scenario and receptor.

Table 4.1 Dose and Risk Summary for All Scenarios

Receptor	GSM	Exposure Duration (years)	Exposure Dose (mrem)	Estimated Cancer Risk	Background Dose from Exposure Duration (mrem)	Exposure Dose Percentage of Background Dose (%)
Reasonable Maximum Exposure Scenarios						
Road Construction Worker	PG in Road Base	5	110	0.5 in 10,000	1550	7%
Road User (Motorist/Bicyclist)	PG in Road Base & Surface	26	28	0.1 in 10,000	8060	0.3%
Truck Driver	PG-Containing Material for Road Base	5	93	0.5 in 10,000	1550	6%
Nearby Resident	PG in Road Base & Surface	26	16	0.08 in 10,000	8060	0.2%
Utility Worker	PG in Road Base	1	0.8	0.004 in 10,000	310	0.3%
	EPA Cancer Risk Management Goal		600	3 in 10,000	600	

Estimated cancer risk below this goal.

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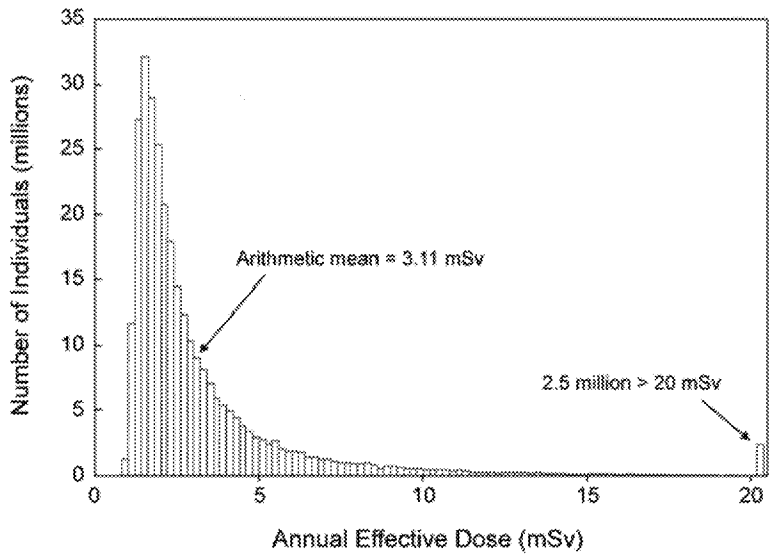
All of the predicted risks for the RME receptors are below the EPAs reference risk factor for new uses of PG of 3 in 10,000. As previously explained, the average annual dose to anyone in the US is about 310 mrem per year (as per NCRP 160). As illustrated in Figure 4.1, there is a wide distribution of dose to people living in the USA arising from natural background sources including, gamma radiation from terrestrial sources and the inhalation of radon and its short-lived decay products. As illustrated in the figure, a substantial number of people living in the US receive an annual dose greater than 10 mSv (i.e., an annual dose greater than 1000 mrem).

Figure 4.1 Background Dose Distribution



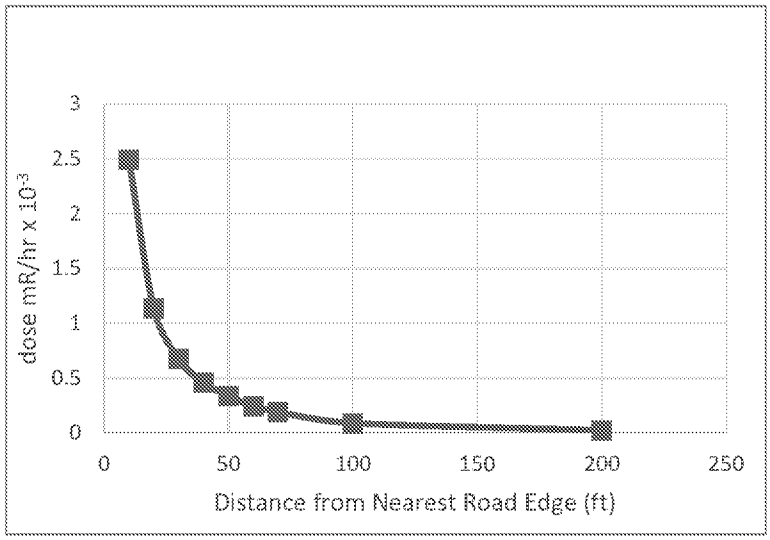
Frequency distribution of annual effective dose (millisievert) for ubiquitous background radiation for members of the U.S. population, 2006. (adapted from Figure 3.20 of NCRP 160)

Risk distribution across a local population is also affected by these factors. The intent of the risk assessment is to predict dose (and risk) for the groups considered likely to be most exposed. The risk assessment does not reflect the general exposures to the entire population. Most public receptors would receive much lower doses than those estimated for these RME receptor groups since most people are located much further from the sources or have shorter exposure periods.

By selecting conservative parameters at the upper end of expected distribution ranges the results are targeted for reasonably extreme cases and do not represent expected results for the more typical local populations of potentially exposed individuals. The assumption of 26 years residency in a home is considered by EPA to be an RME scenario, because it is the upper 90th percentile, i.e., 90 percent of people live in the same home for 26 years or less (EPA 2014). The assumption of a 1:1 ratio mixing of PG with local construction road base materials (sands for example), the EPA assumed a 1:2 mixing of PG with native soils; and the assumption that the proximate resident lives in a home 50 ft from the edge of the road (EPA assumed 330 ft or 100 m).

Exposures and dose are highly dependent on proximity to the PG road and exposure and decrease rapidly with distance from the road as clearly illustrated in the following Figure 4.2.

Figure 4.2 Dose Rate with Distance from Road



Dose vs distance from edge of road at height of 1 m above road surface.

As previously noted, external gamma dose is the dominant contributor to dose. Thus, the incremental dose attributed to PG in a road rapidly becomes lost in the natural dose from background (i.e., there is no additional risk beyond a few hundred ft from the edge of the road).

Thus, other individuals possibly exposed are expected to have notable reductions of exposure duration or proximity results dose well below reasonable maximum scenario values.

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5 CONCLUSIONS

The risk assessment for use of PG in road construction is based on EPA guidance and regulation regarding the appropriate risk benchmark for judging reuse of PG. Specifically, the current risk assessment adopts the EPA's target that

> *"...certain uses of phosphogypsum may be considered acceptable so long as those uses are restricted to limit the estimated lifetime risk to any individual to no more than 3 in 10 thousand" (see the Petition for a full discussion of the regulatory history).*

The annual doses to an RME receptor for each of the scenarios was estimated for both annual exposure and for the assumed duration of total exposure. The total exposure risks were estimated based on duration of exposure for each of the scenarios and receptors.

The results discussed in the previous sections of this report are generally dominated by gamma radiation exposure, which is sensitive to the proximity of the receptor to the PG based road. The gamma radiation exposure rate is also affected by the shielding created by the upper cover layer of the road above the PG road base. As a result, the highest exposure rates are limited in duration to the construction period.

The factors of proximity and duration associated with the most dominant exposure pathway of gamma radiation from an unshielded road base results in limited opportunities for high exposures, doses and risk. The population will have limited or negligible exposure to unshielded road base.

Table 4-1 provides a summary of the results of the calculation for all receptor scenarios. The annual doses estimated for the various receptors arising from the use of PG in road construction are small. Indeed, they represent a small fraction of the unavoidable dose from natural background radiation of about 310 mrem/yr.

The total dose arising from the full duration of exposure is well below the dose of 600 mrem which is equivalent to the total risk of 3 in 10,000.

Overall, the use of PG in road construction will result in very small doses (to reasonably maximally exposed receptors) and total risks that are well below EPA's reference total risk goal.

It should be noted that the risk assessment was based on a nominal radium-226 value of 27 pCi/g, a value based on previous work by the EPA and published information on radium-226 levels in PG. All other factors the same, the potential doses and risks arising from the use of PG in road construction can be scaled on the basis of relative concentrations of radium-226 in PG. For example, the risks to a road construction worker arising from the use of PG containing, for example, 30 pCi/g of radium-226 would be about 0.5 in 10,000 (i.e., 0.5/10,000 x 30/27).

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This concept is further illustrated in the following Table 5.1 which illustrates how the dose to a road construction worker, the most exposed individual RME considered in the current assessment, scales by concentration of Ra-226 in PG and assuming all other factors remain the same.

Table 5.1 Illustrating Scaling Risks by Ra-226 in PG

Average Ra-226 in PG*** (pCi/g)	Exposure Duration Dose* Mrem	Risk**
10	40.7	0.20 per 10,000
20	81.5	0.41 per 10,000
27	110	0.55 per 10,000
30	122	0.61 per 10,000
35	143	0.71 per 10,000
40	163	0.81 per 10,000
50	204	1.02 per 10,000

*For an assumed duration of construction on PG roads of 5 years. Dose scaled from 110 mrem based on PG concentration (e.g. For 10 pCi/g: 40.7 mrem = 110 mrem x 10/27).

**Risk is calculated for each dose value (e.g. For 10 pCi/g: 40.7 mrem x 5 x 10^{-7} per mrem = 0.2 in 10,000)

*** Although we are not aware of any PG with average Ra-226 concentrations anywhere near 148 pCi/g, such PG could in principle be used for road construction and still achieve the EPAs safe level of a risk of 3 in 10,000.

For context, consider the following comparisons to unavoidable natural background radiation described below.

Background radiation experienced by U.S. citizens is comprised of naturally occurring radiation, other sources such as medical examinations, and exposure to products in commerce also contribute to an individual's exposure. Information on the unavoidable exposures from natural background can help provide perspective on the incremental exposures estimated for the current risk assessment.

There are many sources of information on radiation exposures at the state and national levels. For illustration purposes, this risk assessment uses a value of 310 mrem/year as a national average for naturally occurring radiation as provided by the National Council on Radiation Protection & Measurements (NCRP), Report No. 160 (NCRP Online, September 24, 2019). This information is broadly used by the EPA and others to communicate information on natural background radiation (USEPA, September 24, 2019).

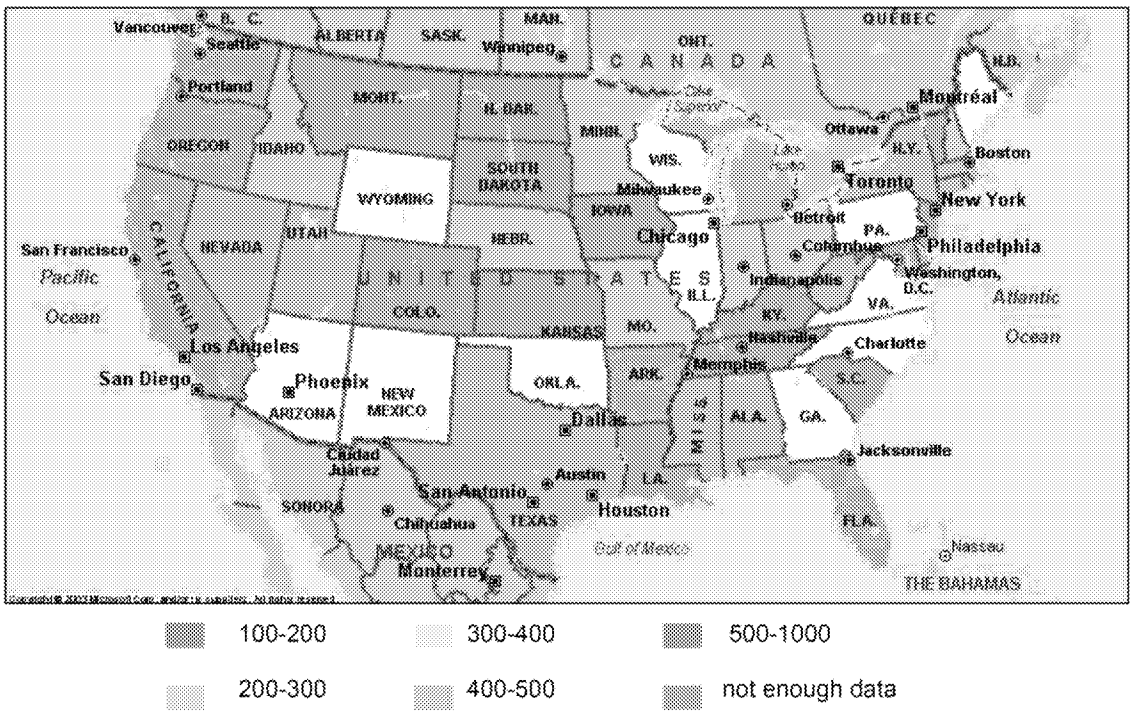
The primary components of naturally occurring background radiation as discussed in NCRP Report No 160 include the following national average values: radon (228 mrem), cosmic (33 rem), internal (i.e., from diet and drink), and terrestrial (21 mrem). While the value of 310 mrem/year provides a national average, naturally occurring background varies widely up to and above 1,000 mrem/year or more as previously illustrated in Figure 4.1.

Natural background doses also vary geographically with some states having higher and some lower naturally occurring exposure levels. Figure 5.1 developed by S. Cohen & Associates (2005) provides an overview of spatial variations in naturally occurring radiation through most states. As shown in the figure,

the ranges used to categorize state levels of naturally occurring background radiation ranges from 100 to more than 1,000 mrem/year for a substantial portion of the US population as previously illustrated.

Figure 5.1 Background Dose Distribution

Figure 2. Average Annual Natural Background Doses (mrem/year) based on Cosmic Radiation, Terrestrial Radiation, and Mean Indoor Radon Levels



Average annual natural background doses (mrem/year) based on cosmic radiation, terrestrial radiation, and mean indoor radon levels (from S Cohen & Associates, 2005)

Table 4-1 provides a summary of the results of the calculation for all receptor scenarios. The annual doses estimated for the various receptors arising from the use of PG in road construction are small and indeed, a small fraction of the unavoidable dose from natural background radiation of about 310 mrem/yr.

The total dose arising from the full duration of exposure is well below the dose of 600 mrem which is equivalent to the total risk of 3 in 10,000.

Overall, the use of PG in road construction will result in very small doses (to reasonably maximally exposed receptors) and risks that are well below EPA's reference risk goal. The use of PG in road construction can be done safely and results in doses that are a small fraction of those arising from natural background radiation.

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APPENDIX A

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APPENDIX A – Bibliography

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APPENDIX B

Excel File with Common and Scenario-Specific Parameters

APPENDIX B – EXCEL FILE WITH COMMON AND SCENARIO-SPECIFIC PARAMETERS

The following tables provide detailed documentation of the assumptions and modelling parameters used throughout this assessment.

Table B-1: Modeling Input Parameters and Assumptions

Parameter	Units	Value	Receptor(s)	Basis/Comments
Title				
Radionuclide transformations	-	ICRP 38	All	
External, inhalation, and ingestion dose conversion factors	-	ICRP 60	All	
Internal dose library	-	ICRP 72 (Adult)	All	
External dose library	-	ICRP 60	All	
Cut-off half life	d	1	All	
Set Pathways				
External gamma (RESRAD)	-	-	RCW, RU, RR	
External gamma (MicroShield®) [1]	-	-	TD, UW, NR	Geometry and receptor location make a MicroShield® better modeling choice.
Incidental Soil Ingestion/Dust Inhalation (RESRAD)	-	-	RCW, NR, UW	
Radon Inhalation (Calculated)	-	-	RR	Equation from U.S. Nuclear Regulatory Commission Regulatory Guidance 3.64 (June 1989)
Soil Concentrations				
PG concentrations	pCi/g	Road Base & Paving		refer to "Rad Concentrations" table
Contaminated Zone				
Area of contaminated zone	m^2	1,500	All	road width = 15 meters, length = 100 meters, area = 1,500 m2
Thickness of contaminated zone (Road base)	m	0.25	RCW, TD, UW	Road base thickness
Thickness of contaminated zone (Decommissioned road base)	m	0.25	RR	Thickness of layer with road base following decommissioning.
Thickness of contaminated zone (Road Surface)	m	0.12	RCW, RU, NR	Road paving thickness
Thickness of contaminated zone (Road base & Surface Shielding)	m	0.25	RCW, RU, NR	Road base thickness
Cover and Contaminated Zone				
Cover depth	m	0	RCW, RU-Paving, NR	No cover
Cover depth	m	0.12	RU-Road base	Paving surface shielding
Cover depth	m	0.3	RR	6 inch cover and 6 inch slab
Density of cover material	g/cm^3	2.25	RR	Road base and surface, construction aggregate, concrete foundation density
Cover erosion rate	m/yr	-	All	No erosion
Density of contaminated zone	g/cm^3	2.25	RCW, RU, UW, NR, RR	Road base and surface, construction aggregate, concrete foundation density
Density of contaminated zone	g/cm^3	1.12	TD	Phosphogypsum density

Table B-1: Modeling Input Parameters and Assumptions

Parameter	Units	Value	Receptor(s)	Basis/Comments
Occupancy				
Inhalation rate	m^3/yr	11,400	RCW, UW	RESRAD 6 User's Manual (2001) Table 2.3; inhalation rate for an industrial worker, assumes an hourly rate of 1.3 m3/hr (EPA 1997)
Inhalation rate	m^3/yr	8,400	NR	RESRAD Onsite 7.2 default
Mass loading for inhalation (worker)	g/cm^3	0.0002	RCW, UW	RESRAD documentation in ANL 2015, Section 3.6.2, pg. 112; upper end of 98th percentile range for PM2.5 concentrations in ambient air.
Mass loading for inhalation (user, resident)	g/cm^3	0.0001	NR	RESRAD Onsite 7.2 default, consistent with EPA BID (100 µg/m3)
Indoor dust filtration factor	-	0.4	NR	RESRAD Onsite 7.2 default
Exposure duration	Receptor-Specific:			Used outside of RESRAD and MicroShield® to determine cancer risks
Road Construction Worker (RCW)	yr	5		
Truck Driver (TD)	yr	5		
Road Users (Motorist/Bicyclist) (RU)	yr	26		
Nearby Resident (NR)	yr	26		
Utility Worker (UW)	yr	1		
Reclaimer Resident (RR)	yr	26		
Outdoor time fraction	Receptor-Specific:			
Road Construction Worker (RCW)	-	0.23		2,000 working hours per year. Fraction = 2,000 hrs /(365 days x 24 hrs/day) = 0.23
Truck Driver (TD)	-	NA		Not needed in MicroShield®
Road Users (Motorist/Bicyclist) (RU)	-	0.06		500 commuting hours per year. Fraction = 500 hrs /(365 days x 24 hrs/day) = 0.06
Nearby Resident (NR)	-	0.25		RESRAD default in ANL 2015, Section 9.6, pg. 246.
Utility Worker (UW)	-	0.018		8 hours/day, 5 days/week, for 4 weeks = 160 working hours per year. Fraction = 160 hrs /(365 days x 24 hrs/day) = 0.018
Reclaimer Resident (RR)	-	0.75		Assumed for consistency with radon model.

Table B-1: Modeling Input Parameters and Assumptions

Parameter	Units	Value	Receptor(s)	Basis/Comments
Shape - External Radiation Area Factors				
Shape of contaminated zone	-	non-circular		
Road Construction Worker (RCW), Road User (RU), Reclaimer Resident (RR) Receptor Location	-	50,50	RCW - Center, RU, RR	Road centered around x=50, y=50, width = 15 m, length = 100 m
Road Construction Worker (RCW) Receptor Location	-	57,50	RCW - Edge	Edge of road at x=57, y=50, width = 15 m, length = 100 m
Ingestion Pathway, Dietary Data				
Incidental soil ingestion rate (worker)	g/yr	82.5	RCW, UW	330 mg/day per OSWER 2014
Incidental soil ingestion rate (nearby resident)	g/yr	36.5	RCW, NR, UW	100 mg/day per OSWER 2014
Radon Inhalation Pathway				
Diffusion coefficient	cm^2/s	0.0004	RR	Rogers et al. (1994)
Radon emanation coefficient	unitless	0.062	RR	Chuahan and Kumar (2015)

Notes:

d = days

g/yr = grams per year

pCi/g = picocuries per gram

m = meters

m^2 = square meters

m^3/yr = cubic meters per year

yr = years

cm^2/s = square centimeter per second

Receptor Codes:

RCW = Road Construction Worker

TD = Truck Driver

RU = Road Users (Motorist/Bicyclist)

NR = Nearby Resident

UW = Utility Worker

RR = Reclaimer (Resident)

[1] See Risk Assessment Report for additional MicroShield® input parameters.

APPENDIX C

RESRAD Output

APPENDIX C – RESRAD OUTPUT

The following RESRAD Output files provide detailed documentation of the modelling runs and results shown within the software.

RESRAD Modelling Results

Road Construction Worker – Road Base No Cover_Center

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Dose Conversion Factor (and Related) Parameter Summary
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
A-1	DCF's for external ground radiation, (mrem/yr)/(pCi/g)			
A-1	At-218 (Source: ICRP 60)	4.878E-03	4.878E-03	DCF1(1)
A-1	Bi-210 (Source: ICRP 60)	5.476E-03	5.476E-03	DCF1(2)
A-1	Bi-214 (Source: ICRP 60)	9.325E+00	9.325E+00	DCF1(3)
A-1	Pa-234 (Source: ICRP 60)	1.088E+01	1.088E+01	DCF1(4)
A-1	Pa-234m (Source: ICRP 60)	9.867E-02	9.867E-02	DCF1(5)
A-1	Pb-210 (Source: ICRP 60)	1.981E-03	1.981E-03	DCF1(6)
A-1	Pb-214 (Source: ICRP 60)	1.243E+00	1.243E+00	DCF1(7)
A-1	Po-210 (Source: ICRP 60)	4.934E-05	4.934E-05	DCF1(8)
A-1	Po-214 (Source: ICRP 60)	4.840E-04	4.840E-04	DCF1(9)
A-1	Po-218 (Source: ICRP 60)	5.326E-05	5.326E-05	DCF1(10)
A-1	Ra-226 (Source: ICRP 60)	2.915E-02	2.915E-02	DCF1(11)
A-1	Rn-222 (Source: ICRP 60)	2.186E-03	2.186E-03	DCF1(12)
A-1	Th-230 (Source: ICRP 60)	1.071E-03	1.071E-03	DCF1(13)
A-1	Th-234 (Source: ICRP 60)	2.130E-02	2.130E-02	DCF1(14)
A-1	Tl-210 (Source: ICRP 60)	1.661E+01	1.661E+01	DCF1(15)
A-1	U-234 (Source: ICRP 60)	3.439E-04	3.439E-04	DCF1(16)
A-1	U-238 (Source: ICRP 60)	7.961E-05	7.961E-05	DCF1(17)
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Bi-210	3.441E-04	3.441E-04	DCF2(1)
B-1	Pb-210	2.072E-02	2.072E-02	DCF2(2)
B-1	Po-210	1.591E-02	1.591E-02	DCF2(3)
B-1	Ra-226	3.515E-02	3.515E-02	DCF2(4)
B-1	Rn-222+D	1.073E-04	0.000E+00	DCF2(5)
B-1	Th-230	3.700E-01	3.700E-01	DCF2(6)
B-1	Th-234+D	2.849E-05	2.849E-05	DCF2(7)
B-1	U-234	3.478E-02	3.478E-02	DCF2(8)
B-1	U-238	2.960E-02	2.960E-02	DCF2(9)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Bi-210	4.810E-06	4.810E-06	DCF3(1)
D-1	Pb-210	2.553E-03	2.553E-03	DCF3(2)
D-1	Po-210	4.440E-03	4.440E-03	DCF3(3)
D-1	Ra-226	1.036E-03	1.036E-03	DCF3(4)
D-1	Rn-222+D	9.249E-07	0.000E+00	DCF3(5)
D-1	Th-230	7.770E-04	7.770E-04	DCF3(6)
D-1	Th-234+D	1.259E-05	1.258E-05	DCF3(7)
D-1	U-234	1.813E-04	1.813E-04	DCF3(8)
D-1	U-238	1.665E-04	1.665E-04	DCF3(9)
D-34	Food transfer factors:			
D-34	Bi-210 , plant/soil concentration ratio, dimensionless	1.000E-01	1.000E-01	RTF(1,1)
D-34	Bi-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(1,2)
D-34	Bi-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-04	5.000E-04	RTF(1,3)
D-34				
D-34	Pb-210 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(2,1)
D-34	Pb-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(2,2)
D-34	Pb-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(2,3)
D-34				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(3,1)
D-34	Po-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(3,2)
D-34	Po-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.400E-04	3.400E-04	RTF(3,3)
D-34				
D-34	Ra-226 , plant/soil concentration ratio, dimensionless	4.000E-02	4.000E-02	RTF(4,1)
D-34	Ra-226 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,2)
D-34	Ra-226 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,3)
D-34				
D-34	Rn-222+D , plant/soil concentration ratio, dimensionless	0.000E+00	0.000E+00	RTF(5,1)
D-34	Rn-222+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,2)
D-34	Rn-222+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,3)
D-34				
D-34	Th-230 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(6,1)
D-34	Th-230 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(6,2)
D-34	Th-230 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(6,3)
D-34				
D-34	Th-234+D , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(7,1)
D-34	Th-234+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(7,2)
D-34	Th-234+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	U-234 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(8,1)
D-34	U-234 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(8,2)
D-34	U-234 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(8,3)
D-34				
D-34	U-238 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(9,1)
D-34	U-238 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(9,2)
D-34	U-238 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(9,3)
D-5	Bioaccumulation factors, fresh water, L/kg:			
D-5	Bi-210 , fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Bi-210 , crustacea and mollusks	1.000E+01	1.000E+01	BIOFAC(1,2)
D-5				
D-5	Pb-210 , fish	3.000E+02	3.000E+02	BIOFAC(2,1)
D-5	Pb-210 , crustacea and mollusks	1.000E+02	1.000E+02	BIOFAC(2,2)
D-5				
D-5	Po-210 , fish	1.000E+02	1.000E+02	BIOFAC(3,1)
D-5	Po-210 , crustacea and mollusks	2.000E+04	2.000E+04	BIOFAC(3,2)
D-5				
D-5	Ra-226 , fish	5.000E+01	5.000E+01	BIOFAC(4,1)
D-5	Ra-226 , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(4,2)
D-5				
D-5	Rn-222+D , fish	0.000E+00	0.000E+00	BIOFAC(5,1)
D-5	Rn-222+D , crustacea and mollusks	0.000E+00	0.000E+00	BIOFAC(5,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(6,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(6,2)
D-5				
D-5	Th-234+D , fish	1.000E+02	1.000E+02	BIOFAC(7,1)
D-5	Th-234+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(7,2)
D-5				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-5	U-234 , fish	1.000E+01	1.000E+01	BIOFAC(8,1)
D-5	U-234 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(8,2)
D-5				
D-5	U-238 , fish	1.000E+01	1.000E+01	BIOFAC(9,1)
D-5	U-238 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(9,2)

#For DCF1(xxx) only, factors are for infinite depth & area. See ETFG table in Ground Pathway of Detailed Report.
*Base Case means Default.Lib w/o Associate Nuclide contributions.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.500E+03	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	2.500E-01	2.000E+00	---	THICK0
R011	Fraction of contamination that is submerged	0.000E+00	0.000E+00	---	SUBMFRACT
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	not used	3.000E+00	---	T(3)
R011	Times for calculations (yr)	not used	1.000E+01	---	T(4)
R011	Times for calculations (yr)	not used	3.000E+01	---	T(5)
R011	Times for calculations (yr)	not used	1.000E+02	---	T(6)
R011	Times for calculations (yr)	not used	3.000E+02	---	T(7)
R011	Times for calculations (yr)	not used	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Bi-210	1.350E+01	0.000E+00	---	S1(1)
R012	Initial principal radionuclide (pCi/g): Pb-210	1.350E+01	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Po-210	1.350E+01	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Ra-226	1.350E+01	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Rn-222	1.350E+01	0.000E+00	---	S1(5)
R012	Initial principal radionuclide (pCi/g): Th-230	2.500E+00	0.000E+00	---	S1(6)
R012	Initial principal radionuclide (pCi/g): Th-234	1.500E+00	0.000E+00	---	S1(7)
R012	Initial principal radionuclide (pCi/g): U-234	1.600E+00	0.000E+00	---	S1(8)
R012	Initial principal radionuclide (pCi/g): U-238	1.500E+00	0.000E+00	---	S1(9)
R012	Concentration in groundwater (pCi/L): Bi-210	not used	0.000E+00	---	W1(1)
R012	Concentration in groundwater (pCi/L): Pb-210	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Po-210	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Rn-222	not used	0.000E+00	---	W1(5)
R012	Concentration in groundwater (pCi/L): Th-230	not used	0.000E+00	---	W1(6)
R012	Concentration in groundwater (pCi/L): Th-234	not used	0.000E+00	---	W1(7)
R012	Concentration in groundwater (pCi/L): U-234	not used	0.000E+00	---	W1(8)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(9)
R013	Cover depth (m)	0.000E+00	0.000E+00	---	COVER0
R013	Density of cover material (g/cm**3)	not used	1.500E+00	---	DENSCV
R013	Cover depth erosion rate (m/yr)	not used	1.000E-03	---	VCV
R013	Density of contaminated zone (g/cm**3)	2.250E+00	1.500E+00	---	DENSCZ
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCZ
R013	Contaminated zone total porosity	4.000E-01	4.000E-01	---	TPCZ
R013	Contaminated zone field capacity	2.000E-01	2.000E-01	---	FCCZ
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01	---	HCCZ
R013	Contaminated zone b parameter	5.300E+00	5.300E+00	---	BCZ
R013	Average annual wind speed (m/sec)	2.000E+00	2.000E+00	---	WIND
R013	Humidity in air (g/m**3)	not used	8.000E+00	---	HUMID
R013	Evapotranspiration coefficient	5.000E-01	5.000E-01	---	EVAPTR
R013	Precipitation (m/yr)	1.000E+00	1.000E+00	---	PRECIP
R013	Irrigation (m/yr)	2.000E-01	2.000E-01	---	RI
R013	Irrigation mode	overhead	overhead	---	IDITCH

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R013	Runoff coefficient	2.000E-01	2.000E-01	---	RUNOFF
R013	Watershed area for nearby stream or pond (m**2)	not used	1.000E+06	---	WAREA
R013	Accuracy for water/soil computations	not used	1.000E-03	---	EPS
R014	Density of saturated zone (g/cm**3)	not used	1.500E+00	---	DENSAQ
R014	Saturated zone total porosity	not used	4.000E-01	---	TPSZ
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Bi-210				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)
R016	Distribution coefficients for Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.876E-03	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(3)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(3,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(3)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.764E-02	ALEACH(3)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(3)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Ra-226				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(4)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(4,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(4)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.267E-02	ALEACH(4)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(4)
R016	Distribution coefficients for Rn-222				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(5)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(5,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(5)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(5)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(5)
R016	Distribution coefficients for Th-230				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(6)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(6,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(6)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(6)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(6)
R016	Distribution coefficients for Th-234				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(7)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(7,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(7)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(7)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(7)
R016	Distribution coefficients for U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(8)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(8,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(8)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(8)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(8)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R017	Inhalation rate (m**3/yr)	1.140E+04	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	2.000E-04	1.000E-04	---	MLINH
R017	Exposure duration	1.000E+00	3.000E+01	---	ED
R017	Shielding factor, inhalation	4.000E-01	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	7.000E-01	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	0.000E+00	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	2.300E-01	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	-1.000E+00	1.000E+00	-1 shows non-circular AREA.	FS

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	4.250E+00	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	8.500E+00	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	1.275E+01	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	1.700E+01	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	2.125E+01	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	2.550E+01	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	2.975E+01	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	3.400E+01	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	3.825E+01	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	4.250E+01	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	4.675E+01	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	5.100E+01	0.000E+00	---	RAD_SHAPE(12)
R017	Fractions of annular areas within AREA:				
R017	Ring 1	1.000E+00	1.000E+00	---	FRACA(1)
R017	Ring 2	1.000E+00	2.732E-01	---	FRACA(2)
R017	Ring 3	5.000E-01	0.000E+00	---	FRACA(3)
R017	Ring 4	3.400E-01	0.000E+00	---	FRACA(4)
R017	Ring 5	2.600E-01	0.000E+00	---	FRACA(5)
R017	Ring 6	2.100E-01	0.000E+00	---	FRACA(6)
R017	Ring 7	1.800E-01	0.000E+00	---	FRACA(7)
R017	Ring 8	1.500E-01	0.000E+00	---	FRACA(8)
R017	Ring 9	1.400E-01	0.000E+00	---	FRACA(9)
R017	Ring 10	1.200E-01	0.000E+00	---	FRACA(10)
R017	Ring 11	1.100E-01	0.000E+00	---	FRACA(11)
R017	Ring 12	7.100E-02	0.000E+00	---	FRACA(12)
R018	Fruits, vegetables and grain consumption (kg/yr)	not used	1.600E+02	---	DIET(1)
R018	Leafy vegetable consumption (kg/yr)	not used	1.400E+01	---	DIET(2)
R018	Milk consumption (L/yr)	not used	9.200E+01	---	DIET(3)
R018	Meat and poultry consumption (kg/yr)	not used	6.300E+01	---	DIET(4)
R018	Fish consumption (kg/yr)	not used	5.400E+00	---	DIET(5)
R018	Other seafood consumption (kg/yr)	not used	9.000E-01	---	DIET(6)
R018	Soil ingestion rate (g/yr)	8.250E+01	3.650E+01	---	SOIL
R018	Drinking water intake (L/yr)	not used	5.100E+02	---	DWI
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)
R19B	Translocation Factor for Fodder	not used	1.000E+00	---	TIV(3)
R19B	Dry Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RDRY(1)
R19B	Dry Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RDRY(2)
R19B	Dry Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RDRY(3)
R19B	Wet Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RWET(1)
R19B	Wet Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RWET(2)
R19B	Wet Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RWET(3)
R19B	Weathering Removal Constant for Vegetation	not used	2.000E+01	---	WLAM
C14	C-12 concentration in water (g/cm**3)	not used	2.000E-05	---	C12WTR
C14	C-12 concentration in contaminated soil (g/g)	not used	3.000E-02	---	C12CZ
C14	Fraction of vegetation carbon from soil	not used	2.000E-02	---	CSOIL
C14	Fraction of vegetation carbon from air	not used	9.800E-01	---	CAIR
C14	C-14 evasion layer thickness in soil (m)	not used	3.000E-01	---	DMC
C14	C-14 evasion flux rate from soil (1/sec)	not used	7.000E-07	---	EVSN
C14	C-12 evasion flux rate from soil (1/sec)	not used	1.000E-10	---	REVSN
C14	Fraction of grain in beef cattle feed	not used	8.000E-01	---	AVFG4
C14	Fraction of grain in milk cow feed	not used	2.000E-01	---	AVFG5
STOR	Storage times of contaminated foodstuffs (days):				
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS
TITL	Maximum number of integration points for dose	17	---	---	LYMAX
TITL	Maximum number of integration points for risk	257	---	---	KYMAX

Summary of Pathway Selections

Pathway	User Selection
1 -- external gamma	active
2 -- inhalation (w/o radon)	active
3 -- plant ingestion	suppressed
4 -- meat ingestion	suppressed
5 -- milk ingestion	suppressed
6 -- aquatic foods	suppressed
7 -- drinking water	suppressed
8 -- soil ingestion	active
9 -- radon	suppressed
Find peak pathway doses	suppressed

Summary : Road Construction Worker - PG in Road Base (Center)
File : C:\USERS\NEMICKASH\DESKTOP\FERTILIZER INSTITUTE\RESRAD\RCW_RB_CENTER070319.RAD

Contaminated Zone Dimensions	
Area:	1500.00 square meters
Thickness:	0.25 meters
Cover Depth:	0.00 meters

Initial Soil Concentrations, pCi/g	
Bi-210	1.350E+01
Pb-210	1.350E+01
Po-210	1.350E+01
Ra-226	1.350E+01
Rn-222	1.350E+01
Th-230	2.500E+00
Th-234	1.500E+00
U-234	1.600E+00
U-238	1.500E+00

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 2.500E+01 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0.000E+00	1.000E+00
TDOSE(t):	2.866E+01	2.817E+01
M(t):	1.146E+00	1.127E+00

Maximum TDOSE(t): 2.866E+01 mrem/yr at t = 0.000E+00 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	3.596E-04	0.0000	2.284E-04	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.603E-02	0.0006
Pb-210	1.864E-02	0.0007	2.738E-02	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.157E+00	0.0404
Po-210	6.047E-05	0.0000	6.972E-03	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.060E-01	0.0177
Ra-226	2.581E+01	0.9007	3.484E-02	0.0012	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.780E-01	0.0097
Rn-222	6.296E-01	0.0220	1.379E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.907E-04	0.0000
Th-230	1.592E-03	0.0001	6.748E-02	0.0024	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.687E-02	0.0013
Th-234	4.563E-03	0.0002	2.980E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.413E-05	0.0000
U-234	1.155E-04	0.0000	4.024E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.456E-03	0.0002
U-238	4.300E-02	0.0015	3.213E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.019E-03	0.0002
Total	2.651E+01	0.9250	1.442E-01	0.0050	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.004E+00	0.0700

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.662E-02	0.0006
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.203E+00	0.0420
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.131E-01	0.0179
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.612E+01	0.9116
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.301E-01	0.0220
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.059E-01	0.0037
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.598E-03	0.0002
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.596E-03	0.0003
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.123E-02	0.0018
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.866E+01	1.0000

*Sum of all water independent and dependent pathways.

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	2.967E-07	0.0000	3.420E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.483E-03	0.0001
Pb-210	1.826E-02	0.0006	3.140E-02	0.0011	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.480E+00	0.0525
Po-210	8.890E-06	0.0000	1.025E-03	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.440E-02	0.0026
Ra-226	2.604E+01	0.9244	3.524E-02	0.0013	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.131E-01	0.0111
Rn-222	7.838E-06	0.0000	1.347E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.347E-04	0.0000
Th-230	3.694E-03	0.0001	6.748E-02	0.0024	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.689E-02	0.0013
Th-234	1.250E-07	0.0000	1.010E-09	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.294E-09	0.0000
U-234	1.134E-04	0.0000	3.954E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.360E-03	0.0002
U-238	4.674E-02	0.0017	3.157E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.964E-03	0.0002
Total	2.611E+01	0.9269	1.423E-01	0.0051	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.918E+00	0.0681

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.517E-03	0.0001
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.530E+00	0.0543
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.543E-02	0.0027
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.639E+01	0.9368
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.560E-04	0.0000
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.081E-01	0.0038
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.284E-07	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.428E-03	0.0003
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.486E-02	0.0019
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.817E+01	1.0000

*Sum of all water independent and dependent pathways.

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
Bi-210	Bi-210	1.000E+00	2.920E-05	6.626E-30	
Bi-210	Po-210	1.000E+00	1.202E-03	1.864E-04	
Bi-210	∑DSR(j)		1.231E-03	1.864E-04	
Pb-210	Pb-210	1.000E+00	4.938E-02	4.744E-02	
Pb-210	Bi-210	1.000E+00	1.070E-03	1.053E-03	
Pb-210	Po-210	1.000E+00	3.863E-02	6.483E-02	
Pb-210	∑DSR(j)		8.908E-02	1.133E-01	
Po-210	Po-210	1.000E+00	3.800E-02	5.587E-03	
Ra-226	Ra-226	1.000E+00	2.815E-02	2.778E-02	
Ra-226	Rn-222+D	1.000E+00	1.906E+00	1.923E+00	
Ra-226	Pb-210	1.000E+00	6.841E-04	2.042E-03	
Ra-226	Bi-210	1.000E+00	1.464E-05	4.476E-05	
Ra-226	Po-210	1.000E+00	3.937E-04	1.962E-03	
Ra-226	∑DSR(j)		1.935E+00	1.955E+00	
Rn-222+D	Rn-222+D	1.000E+00	4.664E-02	1.605E-33	
Rn-222+D	Pb-210	1.000E+00	2.073E-05	2.037E-05	
Rn-222+D	Bi-210	1.000E+00	4.566E-07	4.520E-07	
Rn-222+D	Po-210	1.000E+00	1.622E-05	2.777E-05	
Rn-222+D	∑DSR(j)		4.667E-02	4.859E-05	
Th-230	Th-230	1.000E+00	4.196E-02	4.196E-02	
Th-230	Ra-226	1.000E+00	6.111E-06	1.823E-05	
Th-230	Rn-222+D	1.000E+00	4.115E-04	1.250E-03	
Th-230	Pb-210	1.000E+00	9.787E-08	6.908E-07	
Th-230	Bi-210	1.000E+00	2.059E-09	1.498E-08	
Th-230	Po-210	1.000E+00	4.477E-08	5.297E-07	
Th-230	∑DSR(j)		4.238E-02	4.323E-02	
Th-234+D	Th-234+D	1.000E+00	3.065E-03	8.398E-08	
Th-234+D	U-234	1.000E+00	1.465E-09	1.593E-09	
Th-234+D	Th-230	1.000E+00	4.196E-14	1.413E-13	
Th-234+D	Ra-226	1.000E+00	3.768E-18	3.032E-17	
Th-234+D	Rn-222+D	1.000E+00	2.494E-16	2.060E-15	
Th-234+D	Pb-210	1.000E+00	4.143E-20	7.509E-19	
Th-234+D	Bi-210	1.000E+00	8.522E-22	1.609E-20	
Th-234+D	Po-210	1.000E+00	1.480E-20	4.721E-19	
Th-234+D	∑DSR(j)		3.065E-03	8.557E-08	

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00
U-234	U-234	1.000E+00	5.997E-03	5.892E-03
U-234	Th-230	1.000E+00	1.878E-07	5.588E-07
U-234	Ra-226	1.000E+00	1.827E-11	1.268E-10
U-234	Rn-222+D	1.000E+00	1.214E-09	8.622E-09
U-234	Pb-210	1.000E+00	2.171E-13	3.302E-12
U-234	Bi-210	1.000E+00	4.491E-15	7.088E-14
U-234	Po-210	1.000E+00	8.226E-14	2.137E-12
U-234	∑DSR(j)		5.997E-03	5.892E-03
U-238	U-238	5.400E-05	2.856E-07	2.806E-07
U-238	U-238	9.999E-01	5.289E-03	5.196E-03
U-238	Th-234+D	9.999E-01	2.887E-02	3.138E-02
U-238	U-234	9.999E-01	7.022E-09	2.347E-08
U-238	Th-230	9.999E-01	1.352E-13	1.086E-12
U-238	Ra-226	9.999E-01	9.173E-18	1.618E-16
U-238	Rn-222+D	9.999E-01	5.988E-16	1.090E-14
U-238	Pb-210	9.999E-01	8.014E-20	3.092E-18
U-238	Bi-210	9.999E-01	1.620E-21	6.562E-20
U-238	Po-210	9.999E-01	2.439E-20	1.691E-18
U-238	∑DSR(j)		3.416E-02	3.657E-02

The DSR includes contributions from associated (half-life ≤ 1 day) daughters.

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00
Bi-210	2.031E+04	1.341E+05
Pb-210	2.807E+02	2.206E+02
Po-210	6.578E+02	4.474E+03
Ra-226	1.292E+01	1.279E+01
Rn-222	5.356E+02	5.145E+05
Th-230	5.899E+02	5.783E+02
Th-234	8.156E+03	2.922E+08
U-234	4.169E+03	4.243E+03
U-238	7.319E+02	6.836E+02

Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Nuclide (i)	Initial (pCi/g)	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
Bi-210	1.350E+01	0.000E+00	1.231E-03	2.031E+04	1.231E-03	2.031E+04
Pb-210	1.350E+01	1.000E+00	1.133E-01	2.206E+02	8.908E-02	2.807E+02
Po-210	1.350E+01	0.000E+00	3.800E-02	6.578E+02	3.800E-02	6.578E+02
Ra-226	1.350E+01	0.0864 ± 0.0002	1.975E+00	1.266E+01	1.935E+00	1.292E+01
Rn-222	1.350E+01	0.000E+00	4.667E-02	5.356E+02	4.667E-02	5.356E+02
Th-230	2.500E+00	1.000E+00	4.323E-02	5.783E+02	4.238E-02	5.899E+02
Th-234	1.500E+00	0.000E+00	3.065E-03	8.156E+03	3.065E-03	8.156E+03
U-234	1.600E+00	0.000E+00	5.997E-03	4.169E+03	5.997E-03	4.169E+03
U-238	1.500E+00	0.3657 ± 0.0007	3.692E-02	6.772E+02	3.416E-02	7.319E+02

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	3.943E-04	8.116E-29
Bi-210	Pb-210	1.000E+00	1.444E-02	1.421E-02
Bi-210	Ra-226	1.000E+00	1.977E-04	6.043E-04
Bi-210	Rn-222	1.000E+00	6.164E-06	6.102E-06
Bi-210	Th-230	1.000E+00	5.147E-09	3.745E-08
Bi-210	Th-234	1.000E+00	1.278E-21	2.414E-20
Bi-210	U-234	1.000E+00	7.185E-15	1.134E-13
Bi-210	U-238	9.999E-01	2.430E-21	9.843E-20
Bi-210	∑DOSE(j)		1.504E-02	1.482E-02
Po-210	Bi-210	1.000E+00	1.622E-02	2.517E-03
Po-210	Pb-210	1.000E+00	5.215E-01	8.752E-01
Po-210	Po-210	1.000E+00	5.131E-01	7.543E-02
Po-210	Ra-226	1.000E+00	5.315E-03	2.648E-02
Po-210	Rn-222	1.000E+00	2.190E-04	3.750E-04
Po-210	Th-230	1.000E+00	1.119E-07	1.324E-06
Po-210	Th-234	1.000E+00	2.220E-20	7.081E-19
Po-210	U-234	1.000E+00	1.316E-13	3.419E-12
Po-210	U-238	9.999E-01	3.658E-20	2.537E-18
Po-210	∑DOSE(j)		1.056E+00	9.800E-01
Pb-210	Pb-210	1.000E+00	6.666E-01	6.405E-01
Pb-210	Ra-226	1.000E+00	9.236E-03	2.756E-02
Pb-210	Rn-222	1.000E+00	2.798E-04	2.749E-04
Pb-210	Th-230	1.000E+00	2.447E-07	1.727E-06
Pb-210	Th-234	1.000E+00	6.214E-20	1.126E-18
Pb-210	U-234	1.000E+00	3.474E-13	5.284E-12
Pb-210	U-238	9.999E-01	1.202E-19	4.638E-18
Pb-210	∑DOSE(j)		6.761E-01	6.683E-01
Ra-226	Ra-226	1.000E+00	3.800E-01	3.751E-01
Ra-226	Th-230	1.000E+00	1.528E-05	4.556E-05
Ra-226	Th-234	1.000E+00	5.652E-18	4.548E-17
Ra-226	U-234	1.000E+00	2.924E-11	2.029E-10
Ra-226	U-238	9.999E-01	1.376E-17	2.428E-16
Ra-226	∑DOSE(j)		3.800E-01	3.751E-01
Rn-222	Ra-226	1.000E+00	2.573E+01	2.596E+01
Rn-222	Rn-222	1.000E+00	6.296E-01	0.000E+00
Rn-222	Th-230	1.000E+00	1.029E-03	3.124E-03
Rn-222	Th-234	1.000E+00	3.741E-16	3.089E-15
Rn-222	U-234	1.000E+00	1.942E-09	1.379E-08
Rn-222	U-238	9.999E-01	8.982E-16	1.636E-14
Rn-222	∑DOSE(j)		2.636E+01	2.596E+01
Th-230	Th-230	1.000E+00	1.049E-01	1.049E-01
Th-230	Th-234	1.000E+00	6.294E-14	2.120E-13
Th-230	U-234	1.000E+00	3.004E-07	8.941E-07
Th-230	U-238	9.999E-01	2.027E-13	1.629E-12
Th-230	∑DOSE(j)		1.049E-01	1.049E-01

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	4.598E-03	1.260E-07
Th-234	U-238	9.999E-01	4.330E-02	4.706E-02
Th-234	∑DOSE(j)		4.790E-02	4.706E-02
U-234	Th-234	1.000E+00	2.198E-09	2.389E-09
U-234	U-234	1.000E+00	9.595E-03	9.427E-03
U-234	U-238	9.999E-01	1.053E-08	3.521E-08
U-234	∑DOSE(j)		9.595E-03	9.427E-03
U-238	U-238	5.400E-05	4.284E-07	4.209E-07
U-238	U-238	9.999E-01	7.933E-03	7.794E-03
U-238	∑DOSE(j)		7.934E-03	7.794E-03

THF(i) is the thread fraction of the parent nuclide.

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.350E+01	3.063E-24
Bi-210	Pb-210	1.000E+00	0.000E+00	1.155E+01
Bi-210	Ra-226	1.000E+00	0.000E+00	3.223E-01
Bi-210	Rn-222	1.000E+00	0.000E+00	4.960E-03
Bi-210	Th-230	1.000E+00	0.000E+00	1.264E-05
Bi-210	Th-234	1.000E+00	0.000E+00	4.515E-18
Bi-210	U-234	1.000E+00	0.000E+00	2.353E-11
Bi-210	U-238	9.999E-01	0.000E+00	1.067E-17
Bi-210	∑S(j):		1.350E+01	1.188E+01
Po-210	Bi-210	1.000E+00	0.000E+00	6.623E-02
Po-210	Pb-210	1.000E+00	0.000E+00	9.479E+00
Po-210	Po-210	1.000E+00	1.350E+01	1.985E+00
Po-210	Ra-226	1.000E+00	0.000E+00	1.689E-01
Po-210	Rn-222	1.000E+00	0.000E+00	4.049E-03
Po-210	Th-230	1.000E+00	0.000E+00	4.992E-06
Po-210	Th-234	1.000E+00	0.000E+00	1.366E-18
Po-210	U-234	1.000E+00	0.000E+00	7.521E-12
Po-210	U-238	9.999E-01	0.000E+00	2.722E-18
Po-210	∑S(j):		1.350E+01	1.170E+01
Pb-210	Pb-210	1.000E+00	1.350E+01	1.297E+01
Pb-210	Ra-226	1.000E+00	0.000E+00	3.685E-01
Pb-210	Rn-222	1.000E+00	0.000E+00	5.568E-03
Pb-210	Th-230	1.000E+00	0.000E+00	1.471E-05
Pb-210	Th-234	1.000E+00	0.000E+00	5.371E-18
Pb-210	U-234	1.000E+00	0.000E+00	2.786E-11
Pb-210	U-238	9.999E-01	0.000E+00	1.292E-17
Pb-210	∑S(j):		1.350E+01	1.335E+01
Ra-226	Ra-226	1.000E+00	1.350E+01	1.332E+01
Ra-226	Th-230	1.000E+00	0.000E+00	1.076E-03
Ra-226	Th-234	1.000E+00	0.000E+00	6.472E-16
Ra-226	U-234	1.000E+00	0.000E+00	3.088E-09
Ra-226	U-238	9.999E-01	0.000E+00	2.087E-15
Ra-226	∑S(j):		1.350E+01	1.333E+01
Rn-222	Ra-226	1.000E+00	0.000E+00	1.218E+01
Rn-222	Rn-222	1.000E+00	1.350E+01	4.647E-31
Rn-222	Th-230	1.000E+00	0.000E+00	9.699E-04
Rn-222	Th-234	1.000E+00	0.000E+00	5.740E-16
Rn-222	U-234	1.000E+00	0.000E+00	2.746E-09
Rn-222	U-238	9.999E-01	0.000E+00	1.825E-15
Rn-222	∑S(j):		1.350E+01	1.218E+01
Th-230	Th-230	1.000E+00	2.500E+00	2.500E+00
Th-230	Th-234	1.000E+00	0.000E+00	3.270E-12
Th-230	U-234	1.000E+00	0.000E+00	1.428E-05
Th-230	U-238	9.999E-01	0.000E+00	1.567E-11
Th-230	∑S(j):		2.500E+00	2.500E+00

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.500E+00	4.110E-05
Th-234	U-238	9.999E-01	0.000E+00	1.476E+00
Th-234	∑S(j):		1.500E+00	1.476E+00
U-234	Th-234	1.000E+00	0.000E+00	3.983E-07
U-234	U-234	1.000E+00	1.600E+00	1.572E+00
U-234	U-238	9.999E-01	0.000E+00	3.786E-06
U-234	∑S(j):		1.600E+00	1.572E+00
U-238	U-238	5.400E-05	8.100E-05	7.958E-05
U-238	U-238	9.999E-01	1.500E+00	1.474E+00
U-238	∑S(j):		1.500E+00	1.474E+00

THF(i) is the thread fraction of the parent nuclide.

RESCALC.EXE execution time = 23.29 seconds

RESRAD Modelling Results

Road Construction Worker – Road Base No Cover_Edge

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Dose Conversion Factor (and Related) Parameter Summary
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
A-1	DCF's for external ground radiation, (mrem/yr)/(pCi/g)			
A-1	At-218 (Source: ICRP 60)	4.878E-03	4.878E-03	DCF1(1)
A-1	Bi-210 (Source: ICRP 60)	5.476E-03	5.476E-03	DCF1(2)
A-1	Bi-214 (Source: ICRP 60)	9.325E+00	9.325E+00	DCF1(3)
A-1	Pa-234 (Source: ICRP 60)	1.088E+01	1.088E+01	DCF1(4)
A-1	Pa-234m (Source: ICRP 60)	9.867E-02	9.867E-02	DCF1(5)
A-1	Pb-210 (Source: ICRP 60)	1.981E-03	1.981E-03	DCF1(6)
A-1	Pb-214 (Source: ICRP 60)	1.243E+00	1.243E+00	DCF1(7)
A-1	Po-210 (Source: ICRP 60)	4.934E-05	4.934E-05	DCF1(8)
A-1	Po-214 (Source: ICRP 60)	4.840E-04	4.840E-04	DCF1(9)
A-1	Po-218 (Source: ICRP 60)	5.326E-05	5.326E-05	DCF1(10)
A-1	Ra-226 (Source: ICRP 60)	2.915E-02	2.915E-02	DCF1(11)
A-1	Rn-222 (Source: ICRP 60)	2.186E-03	2.186E-03	DCF1(12)
A-1	Th-230 (Source: ICRP 60)	1.071E-03	1.071E-03	DCF1(13)
A-1	Th-234 (Source: ICRP 60)	2.130E-02	2.130E-02	DCF1(14)
A-1	Tl-210 (Source: ICRP 60)	1.661E+01	1.661E+01	DCF1(15)
A-1	U-234 (Source: ICRP 60)	3.439E-04	3.439E-04	DCF1(16)
A-1	U-238 (Source: ICRP 60)	7.961E-05	7.961E-05	DCF1(17)
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Bi-210	3.441E-04	3.441E-04	DCF2(1)
B-1	Pb-210	2.072E-02	2.072E-02	DCF2(2)
B-1	Po-210	1.591E-02	1.591E-02	DCF2(3)
B-1	Ra-226	3.515E-02	3.515E-02	DCF2(4)
B-1	Rn-222+D	1.073E-04	0.000E+00	DCF2(5)
B-1	Th-230	3.700E-01	3.700E-01	DCF2(6)
B-1	Th-234+D	2.849E-05	2.849E-05	DCF2(7)
B-1	U-234	3.478E-02	3.478E-02	DCF2(8)
B-1	U-238	2.960E-02	2.960E-02	DCF2(9)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Bi-210	4.810E-06	4.810E-06	DCF3(1)
D-1	Pb-210	2.553E-03	2.553E-03	DCF3(2)
D-1	Po-210	4.440E-03	4.440E-03	DCF3(3)
D-1	Ra-226	1.036E-03	1.036E-03	DCF3(4)
D-1	Rn-222+D	9.249E-07	0.000E+00	DCF3(5)
D-1	Th-230	7.770E-04	7.770E-04	DCF3(6)
D-1	Th-234+D	1.259E-05	1.258E-05	DCF3(7)
D-1	U-234	1.813E-04	1.813E-04	DCF3(8)
D-1	U-238	1.665E-04	1.665E-04	DCF3(9)
D-34	Food transfer factors:			
D-34	Bi-210 , plant/soil concentration ratio, dimensionless	1.000E-01	1.000E-01	RTF(1,1)
D-34	Bi-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(1,2)
D-34	Bi-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-04	5.000E-04	RTF(1,3)
D-34				
D-34	Pb-210 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(2,1)
D-34	Pb-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(2,2)
D-34	Pb-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(2,3)
D-34				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(3,1)
D-34	Po-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(3,2)
D-34	Po-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.400E-04	3.400E-04	RTF(3,3)
D-34				
D-34	Ra-226 , plant/soil concentration ratio, dimensionless	4.000E-02	4.000E-02	RTF(4,1)
D-34	Ra-226 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,2)
D-34	Ra-226 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,3)
D-34				
D-34	Rn-222+D , plant/soil concentration ratio, dimensionless	0.000E+00	0.000E+00	RTF(5,1)
D-34	Rn-222+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,2)
D-34	Rn-222+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,3)
D-34				
D-34	Th-230 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(6,1)
D-34	Th-230 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(6,2)
D-34	Th-230 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(6,3)
D-34				
D-34	Th-234+D , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(7,1)
D-34	Th-234+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(7,2)
D-34	Th-234+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	U-234 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(8,1)
D-34	U-234 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(8,2)
D-34	U-234 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(8,3)
D-34				
D-34	U-238 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(9,1)
D-34	U-238 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(9,2)
D-34	U-238 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(9,3)
D-5	Bioaccumulation factors, fresh water, L/kg:			
D-5	Bi-210 , fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Bi-210 , crustacea and mollusks	1.000E+01	1.000E+01	BIOFAC(1,2)
D-5				
D-5	Pb-210 , fish	3.000E+02	3.000E+02	BIOFAC(2,1)
D-5	Pb-210 , crustacea and mollusks	1.000E+02	1.000E+02	BIOFAC(2,2)
D-5				
D-5	Po-210 , fish	1.000E+02	1.000E+02	BIOFAC(3,1)
D-5	Po-210 , crustacea and mollusks	2.000E+04	2.000E+04	BIOFAC(3,2)
D-5				
D-5	Ra-226 , fish	5.000E+01	5.000E+01	BIOFAC(4,1)
D-5	Ra-226 , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(4,2)
D-5				
D-5	Rn-222+D , fish	0.000E+00	0.000E+00	BIOFAC(5,1)
D-5	Rn-222+D , crustacea and mollusks	0.000E+00	0.000E+00	BIOFAC(5,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(6,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(6,2)
D-5				
D-5	Th-234+D , fish	1.000E+02	1.000E+02	BIOFAC(7,1)
D-5	Th-234+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(7,2)
D-5				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-5	U-234 , fish	1.000E+01	1.000E+01	BIOFAC(8,1)
D-5	U-234 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(8,2)
D-5				
D-5	U-238 , fish	1.000E+01	1.000E+01	BIOFAC(9,1)
D-5	U-238 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(9,2)

#For DCF1(xxx) only, factors are for infinite depth & area. See ETFG table in Ground Pathway of Detailed Report.
*Base Case means Default.Lib w/o Associate Nuclide contributions.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.500E+03	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	2.500E-01	2.000E+00	---	THICK0
R011	Fraction of contamination that is submerged	0.000E+00	0.000E+00	---	SUBMFRACT
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	not used	3.000E+00	---	T(3)
R011	Times for calculations (yr)	not used	1.000E+01	---	T(4)
R011	Times for calculations (yr)	not used	3.000E+01	---	T(5)
R011	Times for calculations (yr)	not used	1.000E+02	---	T(6)
R011	Times for calculations (yr)	not used	3.000E+02	---	T(7)
R011	Times for calculations (yr)	not used	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Bi-210	1.350E+01	0.000E+00	---	S1(1)
R012	Initial principal radionuclide (pCi/g): Pb-210	1.350E+01	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Po-210	1.350E+01	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Ra-226	1.350E+01	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Rn-222	1.350E+01	0.000E+00	---	S1(5)
R012	Initial principal radionuclide (pCi/g): Th-230	2.500E+00	0.000E+00	---	S1(6)
R012	Initial principal radionuclide (pCi/g): Th-234	1.500E+00	0.000E+00	---	S1(7)
R012	Initial principal radionuclide (pCi/g): U-234	1.600E+00	0.000E+00	---	S1(8)
R012	Initial principal radionuclide (pCi/g): U-238	1.500E+00	0.000E+00	---	S1(9)
R012	Concentration in groundwater (pCi/L): Bi-210	not used	0.000E+00	---	W1(1)
R012	Concentration in groundwater (pCi/L): Pb-210	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Po-210	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Rn-222	not used	0.000E+00	---	W1(5)
R012	Concentration in groundwater (pCi/L): Th-230	not used	0.000E+00	---	W1(6)
R012	Concentration in groundwater (pCi/L): Th-234	not used	0.000E+00	---	W1(7)
R012	Concentration in groundwater (pCi/L): U-234	not used	0.000E+00	---	W1(8)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(9)
R013	Cover depth (m)	0.000E+00	0.000E+00	---	COVER0
R013	Density of cover material (g/cm**3)	not used	1.500E+00	---	DENSCV
R013	Cover depth erosion rate (m/yr)	not used	1.000E-03	---	VCV
R013	Density of contaminated zone (g/cm**3)	2.250E+00	1.500E+00	---	DENSCZ
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCZ
R013	Contaminated zone total porosity	4.000E-01	4.000E-01	---	TPCZ
R013	Contaminated zone field capacity	2.000E-01	2.000E-01	---	FCCZ
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01	---	HCCZ
R013	Contaminated zone b parameter	5.300E+00	5.300E+00	---	BCZ
R013	Average annual wind speed (m/sec)	2.000E+00	2.000E+00	---	WIND
R013	Humidity in air (g/m**3)	not used	8.000E+00	---	HUMID
R013	Evapotranspiration coefficient	5.000E-01	5.000E-01	---	EVAPTR
R013	Precipitation (m/yr)	1.000E+00	1.000E+00	---	PRECIP
R013	Irrigation (m/yr)	2.000E-01	2.000E-01	---	RI
R013	Irrigation mode	overhead	overhead	---	IDITCH

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R013	Runoff coefficient	2.000E-01	2.000E-01	---	RUNOFF
R013	Watershed area for nearby stream or pond (m**2)	not used	1.000E+06	---	WAREA
R013	Accuracy for water/soil computations	not used	1.000E-03	---	EPS
R014	Density of saturated zone (g/cm**3)	not used	1.500E+00	---	DENSAQ
R014	Saturated zone total porosity	not used	4.000E-01	---	TPSZ
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Bi-210				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)
R016	Distribution coefficients for Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.876E-03	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(3)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(3,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(3)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.764E-02	ALEACH(3)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(3)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Ra-226				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(4)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(4,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(4)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.267E-02	ALEACH(4)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(4)
R016	Distribution coefficients for Rn-222				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(5)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(5,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(5)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(5)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(5)
R016	Distribution coefficients for Th-230				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(6)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(6,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(6)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(6)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(6)
R016	Distribution coefficients for Th-234				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(7)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(7,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(7)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(7)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(7)
R016	Distribution coefficients for U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(8)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(8,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(8)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(8)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(8)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R017	Inhalation rate (m**3/yr)	1.140E+04	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	2.000E-04	1.000E-04	---	MLINH
R017	Exposure duration	1.000E+00	3.000E+01	---	ED
R017	Shielding factor, inhalation	4.000E-01	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	7.000E-01	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	0.000E+00	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	2.300E-01	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	-1.000E+00	1.000E+00	-1 shows non-circular AREA.	FS

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	4.417E+00	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	8.833E+00	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	1.325E+01	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	1.767E+01	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	2.208E+01	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	2.650E+01	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	3.092E+01	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	3.533E+01	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	3.975E+01	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	4.417E+01	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	4.858E+01	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	5.300E+01	0.000E+00	---	RAD_SHAPE(12)
R017	Fractions of annular areas within AREA:				
R017	Ring 1	5.000E-01	1.000E+00	---	FRACA(1)
R017	Ring 2	5.000E-01	2.732E-01	---	FRACA(2)
R017	Ring 3	5.000E-01	0.000E+00	---	FRACA(3)
R017	Ring 4	4.400E-01	0.000E+00	---	FRACA(4)
R017	Ring 5	2.800E-01	0.000E+00	---	FRACA(5)
R017	Ring 6	2.200E-01	0.000E+00	---	FRACA(6)
R017	Ring 7	1.800E-01	0.000E+00	---	FRACA(7)
R017	Ring 8	1.500E-01	0.000E+00	---	FRACA(8)
R017	Ring 9	1.300E-01	0.000E+00	---	FRACA(9)
R017	Ring 10	1.200E-01	0.000E+00	---	FRACA(10)
R017	Ring 11	1.100E-01	0.000E+00	---	FRACA(11)
R017	Ring 12	4.600E-02	0.000E+00	---	FRACA(12)
R018	Fruits, vegetables and grain consumption (kg/yr)	not used	1.600E+02	---	DIET(1)
R018	Leafy vegetable consumption (kg/yr)	not used	1.400E+01	---	DIET(2)
R018	Milk consumption (L/yr)	not used	9.200E+01	---	DIET(3)
R018	Meat and poultry consumption (kg/yr)	not used	6.300E+01	---	DIET(4)
R018	Fish consumption (kg/yr)	not used	5.400E+00	---	DIET(5)
R018	Other seafood consumption (kg/yr)	not used	9.000E-01	---	DIET(6)
R018	Soil ingestion rate (g/yr)	8.250E+01	3.650E+01	---	SOIL
R018	Drinking water intake (L/yr)	not used	5.100E+02	---	DWI
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)
R19B	Translocation Factor for Fodder	not used	1.000E+00	---	TIV(3)
R19B	Dry Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RDRY(1)
R19B	Dry Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RDRY(2)
R19B	Dry Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RDRY(3)
R19B	Wet Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RWET(1)
R19B	Wet Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RWET(2)
R19B	Wet Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RWET(3)
R19B	Weathering Removal Constant for Vegetation	not used	2.000E+01	---	WLAM
C14	C-12 concentration in water (g/cm**3)	not used	2.000E-05	---	C12WTR
C14	C-12 concentration in contaminated soil (g/g)	not used	3.000E-02	---	C12CZ
C14	Fraction of vegetation carbon from soil	not used	2.000E-02	---	CSOIL
C14	Fraction of vegetation carbon from air	not used	9.800E-01	---	CAIR
C14	C-14 evasion layer thickness in soil (m)	not used	3.000E-01	---	DMC
C14	C-14 evasion flux rate from soil (1/sec)	not used	7.000E-07	---	EVSN
C14	C-12 evasion flux rate from soil (1/sec)	not used	1.000E-10	---	REVSN
C14	Fraction of grain in beef cattle feed	not used	8.000E-01	---	AVFG4
C14	Fraction of grain in milk cow feed	not used	2.000E-01	---	AVFG5
STOR	Storage times of contaminated foodstuffs (days):				
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS
TITL	Maximum number of integration points for dose	17	---	---	LYMAX
TITL	Maximum number of integration points for risk	257	---	---	KYMAX

Summary of Pathway Selections

Pathway	User Selection
1 -- external gamma	active
2 -- inhalation (w/o radon)	active
3 -- plant ingestion	suppressed
4 -- meat ingestion	suppressed
5 -- milk ingestion	suppressed
6 -- aquatic foods	suppressed
7 -- drinking water	suppressed
8 -- soil ingestion	active
9 -- radon	suppressed
Find peak pathway doses	suppressed

Summary : Road Construction Worker - PG in Road Base (Edge)
File : C:\USERS\NEMICKASH\DESKTOP\FERTILIZER INSTITUTE\RESRAD\RCW_RB_EDGE_070319.RAD

Contaminated Zone Dimensions	
Area:	1500.00 square meters
Thickness:	0.25 meters
Cover Depth:	0.00 meters

Initial Soil Concentrations, pCi/g	
Bi-210	1.350E+01
Pb-210	1.350E+01
Po-210	1.350E+01
Ra-226	1.350E+01
Rn-222	1.350E+01
Th-230	2.500E+00
Th-234	1.500E+00
U-234	1.600E+00
U-238	1.500E+00

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 2.500E+01 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0.000E+00	1.000E+00
TDOSE(t):	1.606E+01	1.576E+01
M(t):	6.422E-01	6.304E-01

Maximum TDOSE(t): 1.606E+01 mrem/yr at t = 0.000E+00 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	1.873E-04	0.0000	2.284E-04	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.603E-02	0.0010
Pb-210	9.695E-03	0.0006	2.738E-02	0.0017	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.157E+00	0.0720
Po-210	3.168E-05	0.0000	6.972E-03	0.0004	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.060E-01	0.0315
Ra-226	1.354E+01	0.8434	3.484E-02	0.0022	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.780E-01	0.0173
Rn-222	3.303E-01	0.0206	1.379E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.907E-04	0.0000
Th-230	8.311E-04	0.0001	6.748E-02	0.0042	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.687E-02	0.0023
Th-234	2.386E-03	0.0001	2.980E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.413E-05	0.0000
U-234	5.958E-05	0.0000	4.024E-03	0.0003	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.456E-03	0.0003
U-238	2.248E-02	0.0014	3.213E-03	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.019E-03	0.0003
Total	1.391E+01	0.8662	1.442E-01	0.0090	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.004E+00	0.1248

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.645E-02	0.0010
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.194E+00	0.0743
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.130E-01	0.0320
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.385E+01	0.8629
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.309E-01	0.0206
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.052E-01	0.0066
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.420E-03	0.0002
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.540E-03	0.0006
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.071E-02	0.0019
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.606E+01	1.0000

*Sum of all water independent and dependent pathways.

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	1.554E-07	0.0000	3.420E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.483E-03	0.0002
Pb-210	9.498E-03	0.0006	3.140E-02	0.0020	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.480E+00	0.0939
Po-210	4.657E-06	0.0000	1.025E-03	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.440E-02	0.0047
Ra-226	1.366E+01	0.8670	3.524E-02	0.0022	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.131E-01	0.0199
Rn-222	4.077E-06	0.0000	1.347E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.347E-04	0.0000
Th-230	1.934E-03	0.0001	6.748E-02	0.0043	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.689E-02	0.0023
Th-234	6.537E-08	0.0000	1.010E-09	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.294E-09	0.0000
U-234	5.854E-05	0.0000	3.954E-03	0.0003	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.360E-03	0.0003
U-238	2.443E-02	0.0016	3.157E-03	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.964E-03	0.0003
Total	1.370E+01	0.8693	1.423E-01	0.0090	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.918E+00	0.1217

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.517E-03	0.0002
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.521E+00	0.0965
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.543E-02	0.0048
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.401E+01	0.8891
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.522E-04	0.0000
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.063E-01	0.0067
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.868E-08	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.373E-03	0.0006
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.255E-02	0.0021
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.576E+01	1.0000

*Sum of all water independent and dependent pathways.

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
Bi-210	Bi-210	1.000E+00	1.651E-05	3.745E-30	
Bi-210	Po-210	1.000E+00	1.202E-03	1.864E-04	
Bi-210	∑DSR(j)		1.218E-03	1.864E-04	
Pb-210	Pb-210	1.000E+00	4.918E-02	4.725E-02	
Pb-210	Bi-210	1.000E+00	6.047E-04	5.951E-04	
Pb-210	Po-210	1.000E+00	3.863E-02	6.483E-02	
Pb-210	∑DSR(j)		8.841E-02	1.127E-01	
Po-210	Po-210	1.000E+00	3.800E-02	5.587E-03	
Ra-226	Ra-226	1.000E+00	2.523E-02	2.490E-02	
Ra-226	Rn-222+D	1.000E+00	9.999E-01	1.009E+00	
Ra-226	Pb-210	1.000E+00	6.814E-04	2.033E-03	
Ra-226	Bi-210	1.000E+00	8.276E-06	2.530E-05	
Ra-226	Po-210	1.000E+00	3.937E-04	1.962E-03	
Ra-226	∑DSR(j)		1.026E+00	1.038E+00	
Rn-222+D	Rn-222+D	1.000E+00	2.447E-02	8.423E-34	
Rn-222+D	Pb-210	1.000E+00	2.064E-05	2.029E-05	
Rn-222+D	Bi-210	1.000E+00	2.581E-07	2.555E-07	
Rn-222+D	Po-210	1.000E+00	1.622E-05	2.777E-05	
Rn-222+D	∑DSR(j)		2.451E-02	4.831E-05	
Th-230	Th-230	1.000E+00	4.185E-02	4.185E-02	
Th-230	Ra-226	1.000E+00	5.476E-06	1.633E-05	
Th-230	Rn-222+D	1.000E+00	2.159E-04	6.558E-04	
Th-230	Pb-210	1.000E+00	9.748E-08	6.881E-07	
Th-230	Bi-210	1.000E+00	1.164E-09	8.466E-09	
Th-230	Po-210	1.000E+00	4.476E-08	5.297E-07	
Th-230	∑DSR(j)		4.207E-02	4.252E-02	
Th-234+D	Th-234+D	1.000E+00	1.613E-03	4.420E-08	
Th-234+D	U-234	1.000E+00	1.457E-09	1.583E-09	
Th-234+D	Th-230	1.000E+00	4.185E-14	1.410E-13	
Th-234+D	Ra-226	1.000E+00	3.377E-18	2.717E-17	
Th-234+D	Rn-222+D	1.000E+00	1.309E-16	1.081E-15	
Th-234+D	Pb-210	1.000E+00	4.126E-20	7.480E-19	
Th-234+D	Bi-210	1.000E+00	4.817E-22	9.096E-21	
Th-234+D	Po-210	1.000E+00	1.480E-20	4.720E-19	
Th-234+D	∑DSR(j)		1.613E-03	4.578E-08	

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
U-234	U-234	1.000E+00	5.962E-03	5.857E-03	
U-234	Th-230	1.000E+00	1.873E-07	5.574E-07	
U-234	Ra-226	1.000E+00	1.638E-11	1.136E-10	
U-234	Rn-222+D	1.000E+00	6.369E-10	4.524E-09	
U-234	Pb-210	1.000E+00	2.163E-13	3.289E-12	
U-234	Bi-210	1.000E+00	2.538E-15	4.006E-14	
U-234	Po-210	1.000E+00	8.226E-14	2.137E-12	
U-234	∑DSR(j)		5.962E-03	5.858E-03	
U-238	U-238	5.400E-05	2.852E-07	2.801E-07	
U-238	U-238	9.999E-01	5.280E-03	5.188E-03	
U-238	Th-234+D	9.999E-01	1.519E-02	1.652E-02	
U-238	U-234	9.999E-01	6.981E-09	2.334E-08	
U-238	Th-230	9.999E-01	1.348E-13	1.083E-12	
U-238	Ra-226	9.999E-01	8.221E-18	1.450E-16	
U-238	Rn-222+D	9.999E-01	3.142E-16	5.721E-15	
U-238	Pb-210	9.999E-01	7.982E-20	3.080E-18	
U-238	Bi-210	9.999E-01	9.157E-22	3.709E-20	
U-238	Po-210	9.999E-01	2.439E-20	1.691E-18	
U-238	∑DSR(j)		2.048E-02	2.170E-02	

The DSR includes contributions from associated (half-life ≤ 1 day) daughters.

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00
Bi-210	2.052E+04	1.341E+05
Pb-210	2.828E+02	2.219E+02
Po-210	6.579E+02	4.475E+03
Ra-226	2.436E+01	2.409E+01
Rn-222	1.020E+03	5.175E+05
Th-230	5.942E+02	5.879E+02
Th-234	1.550E+04	5.460E+08
U-234	4.193E+03	4.268E+03
U-238	1.221E+03	1.152E+03

Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Nuclide (i)	Initial (pCi/g)	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
Bi-210	1.350E+01	0.000E+00	1.218E-03	2.052E+04	1.218E-03	2.052E+04
Pb-210	1.350E+01	1.000E+00	1.127E-01	2.219E+02	8.841E-02	2.828E+02
Po-210	1.350E+01	0.000E+00	3.800E-02	6.579E+02	3.800E-02	6.579E+02
Ra-226	1.350E+01	0.0875 ± 0.0002	1.047E+00	2.387E+01	1.026E+00	2.436E+01
Rn-222	1.350E+01	0.000E+00	2.451E-02	1.020E+03	2.451E-02	1.020E+03
Th-230	2.500E+00	1.000E+00	4.252E-02	5.879E+02	4.207E-02	5.942E+02
Th-234	1.500E+00	0.000E+00	1.613E-03	1.550E+04	1.613E-03	1.550E+04
U-234	1.600E+00	0.000E+00	5.962E-03	4.193E+03	5.962E-03	4.193E+03
U-238	1.500E+00	0.3657 ± 0.0007	2.191E-02	1.141E+03	2.048E-02	1.221E+03

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	2.228E-04	4.227E-29
Bi-210	Pb-210	1.000E+00	8.163E-03	8.034E-03
Bi-210	Ra-226	1.000E+00	1.117E-04	3.415E-04
Bi-210	Rn-222	1.000E+00	3.484E-06	3.449E-06
Bi-210	Th-230	1.000E+00	2.909E-09	2.117E-08
Bi-210	Th-234	1.000E+00	7.225E-22	1.364E-20
Bi-210	U-234	1.000E+00	4.061E-15	6.410E-14
Bi-210	U-238	9.999E-01	1.374E-21	5.563E-20
Bi-210	∑DOSE(j)		8.501E-03	8.379E-03
Po-210	Bi-210	1.000E+00	1.622E-02	2.517E-03
Po-210	Pb-210	1.000E+00	5.215E-01	8.752E-01
Po-210	Po-210	1.000E+00	5.130E-01	7.543E-02
Po-210	Ra-226	1.000E+00	5.315E-03	2.648E-02
Po-210	Rn-222	1.000E+00	2.189E-04	3.749E-04
Po-210	Th-230	1.000E+00	1.119E-07	1.324E-06
Po-210	Th-234	1.000E+00	2.219E-20	7.081E-19
Po-210	U-234	1.000E+00	1.316E-13	3.419E-12
Po-210	U-238	9.999E-01	3.658E-20	2.537E-18
Po-210	∑DOSE(j)		1.056E+00	9.800E-01
Pb-210	Pb-210	1.000E+00	6.639E-01	6.379E-01
Pb-210	Ra-226	1.000E+00	9.199E-03	2.745E-02
Pb-210	Rn-222	1.000E+00	2.787E-04	2.738E-04
Pb-210	Th-230	1.000E+00	2.437E-07	1.720E-06
Pb-210	Th-234	1.000E+00	6.190E-20	1.122E-18
Pb-210	U-234	1.000E+00	3.460E-13	5.263E-12
Pb-210	U-238	9.999E-01	1.197E-19	4.620E-18
Pb-210	∑DOSE(j)		6.734E-01	6.657E-01
Ra-226	Ra-226	1.000E+00	3.406E-01	3.361E-01
Ra-226	Th-230	1.000E+00	1.369E-05	4.083E-05
Ra-226	Th-234	1.000E+00	5.065E-18	4.076E-17
Ra-226	U-234	1.000E+00	2.620E-11	1.818E-10
Ra-226	U-238	9.999E-01	1.233E-17	2.176E-16
Ra-226	∑DOSE(j)		3.406E-01	3.362E-01
Rn-222	Ra-226	1.000E+00	1.350E+01	1.362E+01
Rn-222	Rn-222	1.000E+00	3.304E-01	0.000E+00
Rn-222	Th-230	1.000E+00	5.398E-04	1.639E-03
Rn-222	Th-234	1.000E+00	1.963E-16	1.621E-15
Rn-222	U-234	1.000E+00	1.019E-09	7.238E-09
Rn-222	U-238	9.999E-01	4.713E-16	8.582E-15
Rn-222	∑DOSE(j)		1.383E+01	1.362E+01
Th-230	Th-230	1.000E+00	1.046E-01	1.046E-01
Th-230	Th-234	1.000E+00	6.278E-14	2.115E-13
Th-230	U-234	1.000E+00	2.996E-07	8.918E-07
Th-230	U-238	9.999E-01	2.022E-13	1.625E-12
Th-230	∑DOSE(j)		1.046E-01	1.046E-01

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	2.420E-03	6.630E-08
Th-234	U-238	9.999E-01	2.279E-02	2.477E-02
Th-234	∑DOSE(j)		2.521E-02	2.477E-02
U-234	Th-234	1.000E+00	2.185E-09	2.375E-09
U-234	U-234	1.000E+00	9.539E-03	9.372E-03
U-234	U-238	9.999E-01	1.047E-08	3.501E-08
U-234	∑DOSE(j)		9.539E-03	9.372E-03
U-238	U-238	5.400E-05	4.277E-07	4.202E-07
U-238	U-238	9.999E-01	7.921E-03	7.782E-03
U-238	∑DOSE(j)		7.921E-03	7.782E-03

THF(i) is the thread fraction of the parent nuclide.

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.350E+01	3.063E-24
Bi-210	Pb-210	1.000E+00	0.000E+00	1.155E+01
Bi-210	Ra-226	1.000E+00	0.000E+00	3.223E-01
Bi-210	Rn-222	1.000E+00	0.000E+00	4.960E-03
Bi-210	Th-230	1.000E+00	0.000E+00	1.264E-05
Bi-210	Th-234	1.000E+00	0.000E+00	4.515E-18
Bi-210	U-234	1.000E+00	0.000E+00	2.353E-11
Bi-210	U-238	9.999E-01	0.000E+00	1.067E-17
Bi-210	∑S(j):		1.350E+01	1.188E+01
Po-210	Bi-210	1.000E+00	0.000E+00	6.623E-02
Po-210	Pb-210	1.000E+00	0.000E+00	9.479E+00
Po-210	Po-210	1.000E+00	1.350E+01	1.985E+00
Po-210	Ra-226	1.000E+00	0.000E+00	1.689E-01
Po-210	Rn-222	1.000E+00	0.000E+00	4.049E-03
Po-210	Th-230	1.000E+00	0.000E+00	4.992E-06
Po-210	Th-234	1.000E+00	0.000E+00	1.366E-18
Po-210	U-234	1.000E+00	0.000E+00	7.521E-12
Po-210	U-238	9.999E-01	0.000E+00	2.722E-18
Po-210	∑S(j):		1.350E+01	1.170E+01
Pb-210	Pb-210	1.000E+00	1.350E+01	1.297E+01
Pb-210	Ra-226	1.000E+00	0.000E+00	3.685E-01
Pb-210	Rn-222	1.000E+00	0.000E+00	5.568E-03
Pb-210	Th-230	1.000E+00	0.000E+00	1.471E-05
Pb-210	Th-234	1.000E+00	0.000E+00	5.371E-18
Pb-210	U-234	1.000E+00	0.000E+00	2.786E-11
Pb-210	U-238	9.999E-01	0.000E+00	1.292E-17
Pb-210	∑S(j):		1.350E+01	1.335E+01
Ra-226	Ra-226	1.000E+00	1.350E+01	1.332E+01
Ra-226	Th-230	1.000E+00	0.000E+00	1.076E-03
Ra-226	Th-234	1.000E+00	0.000E+00	6.472E-16
Ra-226	U-234	1.000E+00	0.000E+00	3.088E-09
Ra-226	U-238	9.999E-01	0.000E+00	2.087E-15
Ra-226	∑S(j):		1.350E+01	1.333E+01
Rn-222	Ra-226	1.000E+00	0.000E+00	1.218E+01
Rn-222	Rn-222	1.000E+00	1.350E+01	4.647E-31
Rn-222	Th-230	1.000E+00	0.000E+00	9.699E-04
Rn-222	Th-234	1.000E+00	0.000E+00	5.740E-16
Rn-222	U-234	1.000E+00	0.000E+00	2.746E-09
Rn-222	U-238	9.999E-01	0.000E+00	1.825E-15
Rn-222	∑S(j):		1.350E+01	1.218E+01
Th-230	Th-230	1.000E+00	2.500E+00	2.500E+00
Th-230	Th-234	1.000E+00	0.000E+00	3.270E-12
Th-230	U-234	1.000E+00	0.000E+00	1.428E-05
Th-230	U-238	9.999E-01	0.000E+00	1.567E-11
Th-230	∑S(j):		2.500E+00	2.500E+00

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.500E+00	4.110E-05
Th-234	U-238	9.999E-01	0.000E+00	1.476E+00
Th-234	∑S(j):		1.500E+00	1.476E+00
U-234	Th-234	1.000E+00	0.000E+00	3.983E-07
U-234	U-234	1.000E+00	1.600E+00	1.572E+00
U-234	U-238	9.999E-01	0.000E+00	3.786E-06
U-234	∑S(j):		1.600E+00	1.572E+00
U-238	U-238	5.400E-05	8.100E-05	7.958E-05
U-238	U-238	9.999E-01	1.500E+00	1.474E+00
U-238	∑S(j):		1.500E+00	1.474E+00

THF(i) is the thread fraction of the parent nuclide.

RESCALC.EXE execution time = 23.68 seconds

RESRAD Modelling Results

Road Construction Worker – Road Base with Surface Shield_Center

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Dose Conversion Factor (and Related) Parameter Summary
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
A-1	DCF's for external ground radiation, (mrem/yr)/(pCi/g)			
A-1	At-218 (Source: ICRP 60)	4.878E-03	4.878E-03	DCF1(1)
A-1	Bi-210 (Source: ICRP 60)	5.476E-03	5.476E-03	DCF1(2)
A-1	Bi-214 (Source: ICRP 60)	9.325E+00	9.325E+00	DCF1(3)
A-1	Pa-234 (Source: ICRP 60)	1.088E+01	1.088E+01	DCF1(4)
A-1	Pa-234m (Source: ICRP 60)	9.867E-02	9.867E-02	DCF1(5)
A-1	Pb-210 (Source: ICRP 60)	1.981E-03	1.981E-03	DCF1(6)
A-1	Pb-214 (Source: ICRP 60)	1.243E+00	1.243E+00	DCF1(7)
A-1	Po-210 (Source: ICRP 60)	4.934E-05	4.934E-05	DCF1(8)
A-1	Po-214 (Source: ICRP 60)	4.840E-04	4.840E-04	DCF1(9)
A-1	Po-218 (Source: ICRP 60)	5.326E-05	5.326E-05	DCF1(10)
A-1	Ra-226 (Source: ICRP 60)	2.915E-02	2.915E-02	DCF1(11)
A-1	Rn-222 (Source: ICRP 60)	2.186E-03	2.186E-03	DCF1(12)
A-1	Th-230 (Source: ICRP 60)	1.071E-03	1.071E-03	DCF1(13)
A-1	Th-234 (Source: ICRP 60)	2.130E-02	2.130E-02	DCF1(14)
A-1	Tl-210 (Source: ICRP 60)	1.661E+01	1.661E+01	DCF1(15)
A-1	U-234 (Source: ICRP 60)	3.439E-04	3.439E-04	DCF1(16)
A-1	U-238 (Source: ICRP 60)	7.961E-05	7.961E-05	DCF1(17)
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Bi-210	3.441E-04	3.441E-04	DCF2(1)
B-1	Pb-210	2.072E-02	2.072E-02	DCF2(2)
B-1	Po-210	1.591E-02	1.591E-02	DCF2(3)
B-1	Ra-226	3.515E-02	3.515E-02	DCF2(4)
B-1	Rn-222+D	1.073E-04	0.000E+00	DCF2(5)
B-1	Th-230	3.700E-01	3.700E-01	DCF2(6)
B-1	Th-234+D	2.849E-05	2.849E-05	DCF2(7)
B-1	U-234	3.478E-02	3.478E-02	DCF2(8)
B-1	U-238	2.960E-02	2.960E-02	DCF2(9)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Bi-210	4.810E-06	4.810E-06	DCF3(1)
D-1	Pb-210	2.553E-03	2.553E-03	DCF3(2)
D-1	Po-210	4.440E-03	4.440E-03	DCF3(3)
D-1	Ra-226	1.036E-03	1.036E-03	DCF3(4)
D-1	Rn-222+D	9.249E-07	0.000E+00	DCF3(5)
D-1	Th-230	7.770E-04	7.770E-04	DCF3(6)
D-1	Th-234+D	1.259E-05	1.258E-05	DCF3(7)
D-1	U-234	1.813E-04	1.813E-04	DCF3(8)
D-1	U-238	1.665E-04	1.665E-04	DCF3(9)
D-34	Food transfer factors:			
D-34	Bi-210 , plant/soil concentration ratio, dimensionless	1.000E-01	1.000E-01	RTF(1,1)
D-34	Bi-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(1,2)
D-34	Bi-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-04	5.000E-04	RTF(1,3)
D-34				
D-34	Pb-210 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(2,1)
D-34	Pb-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(2,2)
D-34	Pb-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(2,3)
D-34				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(3,1)
D-34	Po-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(3,2)
D-34	Po-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.400E-04	3.400E-04	RTF(3,3)
D-34				
D-34	Ra-226 , plant/soil concentration ratio, dimensionless	4.000E-02	4.000E-02	RTF(4,1)
D-34	Ra-226 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,2)
D-34	Ra-226 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,3)
D-34				
D-34	Rn-222+D , plant/soil concentration ratio, dimensionless	0.000E+00	0.000E+00	RTF(5,1)
D-34	Rn-222+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,2)
D-34	Rn-222+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,3)
D-34				
D-34	Th-230 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(6,1)
D-34	Th-230 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(6,2)
D-34	Th-230 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(6,3)
D-34				
D-34	Th-234+D , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(7,1)
D-34	Th-234+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(7,2)
D-34	Th-234+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	U-234 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(8,1)
D-34	U-234 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(8,2)
D-34	U-234 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(8,3)
D-34				
D-34	U-238 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(9,1)
D-34	U-238 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(9,2)
D-34	U-238 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(9,3)
D-5	Bioaccumulation factors, fresh water, L/kg:			
D-5	Bi-210 , fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Bi-210 , crustacea and mollusks	1.000E+01	1.000E+01	BIOFAC(1,2)
D-5				
D-5	Pb-210 , fish	3.000E+02	3.000E+02	BIOFAC(2,1)
D-5	Pb-210 , crustacea and mollusks	1.000E+02	1.000E+02	BIOFAC(2,2)
D-5				
D-5	Po-210 , fish	1.000E+02	1.000E+02	BIOFAC(3,1)
D-5	Po-210 , crustacea and mollusks	2.000E+04	2.000E+04	BIOFAC(3,2)
D-5				
D-5	Ra-226 , fish	5.000E+01	5.000E+01	BIOFAC(4,1)
D-5	Ra-226 , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(4,2)
D-5				
D-5	Rn-222+D , fish	0.000E+00	0.000E+00	BIOFAC(5,1)
D-5	Rn-222+D , crustacea and mollusks	0.000E+00	0.000E+00	BIOFAC(5,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(6,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(6,2)
D-5				
D-5	Th-234+D , fish	1.000E+02	1.000E+02	BIOFAC(7,1)
D-5	Th-234+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(7,2)
D-5				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-5	U-234 , fish	1.000E+01	1.000E+01	BIOFAC(8,1)
D-5	U-234 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(8,2)
D-5				
D-5	U-238 , fish	1.000E+01	1.000E+01	BIOFAC(9,1)
D-5	U-238 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(9,2)

#For DCF1(xxx) only, factors are for infinite depth & area. See ETFG table in Ground Pathway of Detailed Report.
*Base Case means Default.Lib w/o Associate Nuclide contributions.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.500E+03	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	2.500E-01	2.000E+00	---	THICK0
R011	Fraction of contamination that is submerged	0.000E+00	0.000E+00	---	SUBMFRACT
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	not used	3.000E+00	---	T(3)
R011	Times for calculations (yr)	not used	1.000E+01	---	T(4)
R011	Times for calculations (yr)	not used	3.000E+01	---	T(5)
R011	Times for calculations (yr)	not used	1.000E+02	---	T(6)
R011	Times for calculations (yr)	not used	3.000E+02	---	T(7)
R011	Times for calculations (yr)	not used	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Bi-210	1.350E+01	0.000E+00	---	S1(1)
R012	Initial principal radionuclide (pCi/g): Pb-210	1.350E+01	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Po-210	1.350E+01	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Ra-226	1.350E+01	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Rn-222	1.350E+01	0.000E+00	---	S1(5)
R012	Initial principal radionuclide (pCi/g): Th-230	2.500E+00	0.000E+00	---	S1(6)
R012	Initial principal radionuclide (pCi/g): Th-234	1.500E+00	0.000E+00	---	S1(7)
R012	Initial principal radionuclide (pCi/g): U-234	1.600E+00	0.000E+00	---	S1(8)
R012	Initial principal radionuclide (pCi/g): U-238	1.500E+00	0.000E+00	---	S1(9)
R012	Concentration in groundwater (pCi/L): Bi-210	not used	0.000E+00	---	W1(1)
R012	Concentration in groundwater (pCi/L): Pb-210	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Po-210	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Rn-222	not used	0.000E+00	---	W1(5)
R012	Concentration in groundwater (pCi/L): Th-230	not used	0.000E+00	---	W1(6)
R012	Concentration in groundwater (pCi/L): Th-234	not used	0.000E+00	---	W1(7)
R012	Concentration in groundwater (pCi/L): U-234	not used	0.000E+00	---	W1(8)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(9)
R013	Cover depth (m)	1.200E-01	0.000E+00	---	COVER0
R013	Density of cover material (g/cm**3)	2.250E+00	1.500E+00	---	DENSCV
R013	Cover depth erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCV
R013	Density of contaminated zone (g/cm**3)	2.250E+00	1.500E+00	---	DENSCZ
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCZ
R013	Contaminated zone total porosity	4.000E-01	4.000E-01	---	TPCZ
R013	Contaminated zone field capacity	2.000E-01	2.000E-01	---	FCCZ
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01	---	HCCZ
R013	Contaminated zone b parameter	5.300E+00	5.300E+00	---	BCZ
R013	Average annual wind speed (m/sec)	2.000E+00	2.000E+00	---	WIND
R013	Humidity in air (g/m**3)	not used	8.000E+00	---	HUMID
R013	Evapotranspiration coefficient	5.000E-01	5.000E-01	---	EVAPTR
R013	Precipitation (m/yr)	1.000E+00	1.000E+00	---	PRECIP
R013	Irrigation (m/yr)	2.000E-01	2.000E-01	---	RI
R013	Irrigation mode	overhead	overhead	---	IDITCH

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R013	Runoff coefficient	2.000E-01	2.000E-01	---	RUNOFF
R013	Watershed area for nearby stream or pond (m**2)	not used	1.000E+06	---	WAREA
R013	Accuracy for water/soil computations	not used	1.000E-03	---	EPS
R014	Density of saturated zone (g/cm**3)	not used	1.500E+00	---	DENSAQ
R014	Saturated zone total porosity	not used	4.000E-01	---	TPSZ
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Bi-210				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)
R016	Distribution coefficients for Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.876E-03	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(3)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(3,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(3)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.764E-02	ALEACH(3)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(3)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Ra-226				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(4)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(4,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(4)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.267E-02	ALEACH(4)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(4)
R016	Distribution coefficients for Rn-222				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(5)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(5,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(5)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(5)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(5)
R016	Distribution coefficients for Th-230				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(6)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(6,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(6)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(6)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(6)
R016	Distribution coefficients for Th-234				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(7)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(7,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(7)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(7)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(7)
R016	Distribution coefficients for U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(8)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(8,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(8)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(8)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(8)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R017	Inhalation rate (m**3/yr)	1.140E+04	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	2.000E-04	1.000E-04	---	MLINH
R017	Exposure duration	1.000E+00	3.000E+01	---	ED
R017	Shielding factor, inhalation	4.000E-01	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	7.000E-01	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	0.000E+00	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	2.300E-01	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	-1.000E+00	1.000E+00	-1 shows non-circular AREA.	FS

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	4.250E+00	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	8.500E+00	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	1.275E+01	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	1.700E+01	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	2.125E+01	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	2.550E+01	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	2.975E+01	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	3.400E+01	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	3.825E+01	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	4.250E+01	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	4.675E+01	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	5.100E+01	0.000E+00	---	RAD_SHAPE(12)
R017	Fractions of annular areas within AREA:				
R017	Ring 1	1.000E+00	1.000E+00	---	FRACA(1)
R017	Ring 2	1.000E+00	2.732E-01	---	FRACA(2)
R017	Ring 3	5.000E-01	0.000E+00	---	FRACA(3)
R017	Ring 4	3.500E-01	0.000E+00	---	FRACA(4)
R017	Ring 5	2.600E-01	0.000E+00	---	FRACA(5)
R017	Ring 6	2.100E-01	0.000E+00	---	FRACA(6)
R017	Ring 7	1.800E-01	0.000E+00	---	FRACA(7)
R017	Ring 8	1.600E-01	0.000E+00	---	FRACA(8)
R017	Ring 9	1.400E-01	0.000E+00	---	FRACA(9)
R017	Ring 10	1.200E-01	0.000E+00	---	FRACA(10)
R017	Ring 11	1.100E-01	0.000E+00	---	FRACA(11)
R017	Ring 12	7.000E-02	0.000E+00	---	FRACA(12)
R018	Fruits, vegetables and grain consumption (kg/yr)	not used	1.600E+02	---	DIET(1)
R018	Leafy vegetable consumption (kg/yr)	not used	1.400E+01	---	DIET(2)
R018	Milk consumption (L/yr)	not used	9.200E+01	---	DIET(3)
R018	Meat and poultry consumption (kg/yr)	not used	6.300E+01	---	DIET(4)
R018	Fish consumption (kg/yr)	not used	5.400E+00	---	DIET(5)
R018	Other seafood consumption (kg/yr)	not used	9.000E-01	---	DIET(6)
R018	Soil ingestion rate (g/yr)	8.250E+01	3.650E+01	---	SOIL
R018	Drinking water intake (L/yr)	not used	5.100E+02	---	DWI
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)
R19B	Translocation Factor for Fodder	not used	1.000E+00	---	TIV(3)
R19B	Dry Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RDRY(1)
R19B	Dry Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RDRY(2)
R19B	Dry Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RDRY(3)
R19B	Wet Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RWET(1)
R19B	Wet Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RWET(2)
R19B	Wet Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RWET(3)
R19B	Weathering Removal Constant for Vegetation	not used	2.000E+01	---	WLAM
C14	C-12 concentration in water (g/cm**3)	not used	2.000E-05	---	C12WTR
C14	C-12 concentration in contaminated soil (g/g)	not used	3.000E-02	---	C12CZ
C14	Fraction of vegetation carbon from soil	not used	2.000E-02	---	CSOIL
C14	Fraction of vegetation carbon from air	not used	9.800E-01	---	CAIR
C14	C-14 evasion layer thickness in soil (m)	not used	3.000E-01	---	DMC
C14	C-14 evasion flux rate from soil (1/sec)	not used	7.000E-07	---	EVSN
C14	C-12 evasion flux rate from soil (1/sec)	not used	1.000E-10	---	REVSN
C14	Fraction of grain in beef cattle feed	not used	8.000E-01	---	AVFG4
C14	Fraction of grain in milk cow feed	not used	2.000E-01	---	AVFG5
STOR	Storage times of contaminated foodstuffs (days):				
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS
TITL	Maximum number of integration points for dose	17	---	---	LYMAX
TITL	Maximum number of integration points for risk	257	---	---	KYMAX

Summary of Pathway Selections

Pathway	User Selection
1 -- external gamma	active
2 -- inhalation (w/o radon)	active
3 -- plant ingestion	suppressed
4 -- meat ingestion	suppressed
5 -- milk ingestion	suppressed
6 -- aquatic foods	suppressed
7 -- drinking water	suppressed
8 -- soil ingestion	active
9 -- radon	suppressed
Find peak pathway doses	suppressed

Summary : Road Construction Worker - PG in Road Base with Shield (Center)
File : C:\USERS\NEMICKASH\DESKTOP\FERTILIZER INSTITUTE\RESRAD\RCW_RBSS_CENTER_070319.RAD

Contaminated Zone Dimensions		Initial Soil Concentrations, pCi/g	
Area:	1500.00 square meters	Bi-210	1.350E+01
Thickness:	0.25 meters	Pb-210	1.350E+01
Cover Depth:	0.12 meters	Po-210	1.350E+01
		Ra-226	1.350E+01
		Rn-222	1.350E+01
		Th-230	2.500E+00
		Th-234	1.500E+00
		U-234	1.600E+00
		U-238	1.500E+00

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 2.500E+01 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0.000E+00	1.000E+00
TDOSE(t):	3.583E+00	3.519E+00
M(t):	1.433E-01	1.407E-01

Maximum TDOSE(t): 3.583E+00 mrem/yr at t = 0.000E+00 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	5.571E-06	0.0000	4.567E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.206E-03	0.0009
Pb-210	2.033E-04	0.0001	5.476E-03	0.0015	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.313E-01	0.0645
Po-210	5.808E-06	0.0000	1.394E-03	0.0004	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.012E-01	0.0282
Ra-226	3.075E+00	0.8581	6.968E-03	0.0019	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.560E-02	0.0155
Rn-222	7.519E-02	0.0210	2.759E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.813E-05	0.0000
Th-230	1.264E-04	0.0000	1.350E-02	0.0038	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.374E-03	0.0021
Th-234	3.256E-04	0.0001	5.961E-08	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.827E-06	0.0000
U-234	4.623E-07	0.0000	8.048E-04	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.091E-03	0.0003
U-238	3.067E-03	0.0009	6.427E-04	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.004E-03	0.0003
Total	3.154E+00	0.8801	2.883E-02	0.0080	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.009E-01	0.1119

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.257E-03	0.0009
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.370E-01	0.0661
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.026E-01	0.0286
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.137E+00	0.8755
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.530E-02	0.0210
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.100E-02	0.0059
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.325E-04	0.0001
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.896E-03	0.0005
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.713E-03	0.0013
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.583E+00	1.0000

*Sum of all water independent and dependent pathways.

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	2.849E-08	0.0000	6.840E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.965E-04	0.0001
Pb-210	2.041E-04	0.0001	6.280E-03	0.0018	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.961E-01	0.0841
Po-210	8.539E-07	0.0000	2.050E-04	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.488E-02	0.0042
Ra-226	3.103E+00	0.8818	7.048E-03	0.0020	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.262E-02	0.0178
Rn-222	8.763E-08	0.0000	2.694E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.269E-04	0.0000
Th-230	3.768E-04	0.0001	1.350E-02	0.0038	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.378E-03	0.0021
Th-234	8.921E-09	0.0000	2.020E-10	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.587E-10	0.0000
U-234	4.556E-07	0.0000	7.908E-04	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.072E-03	0.0003
U-238	3.333E-03	0.0009	6.315E-04	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.928E-04	0.0003
Total	3.107E+00	0.8829	2.846E-02	0.0081	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.836E-01	0.1090

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.034E-04	0.0001
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.025E-01	0.0860
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.509E-02	0.0043
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.172E+00	0.9016
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.297E-04	0.0000
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.125E-02	0.0060
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.582E-09	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.863E-03	0.0005
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.958E-03	0.0014
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.519E+00	1.0000

*Sum of all water independent and dependent pathways.

Summary : Road Construction Worker - PG in Road Base with Shield (Center)
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Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
Bi-210	Bi-210	1.000E+00	9.407E-07	2.134E-31	
Bi-210	Po-210	1.000E+00	2.404E-04	3.729E-05	
Bi-210	∑DSR(j)		2.413E-04	3.729E-05	
Pb-210	Pb-210	1.000E+00	9.794E-03	9.410E-03	
Pb-210	Bi-210	1.000E+00	3.446E-05	3.392E-05	
Pb-210	Po-210	1.000E+00	7.726E-03	1.297E-02	
Pb-210	∑DSR(j)		1.755E-02	2.241E-02	
Po-210	Po-210	1.000E+00	7.600E-03	1.117E-03	
Ra-226	Ra-226	1.000E+00	4.574E-03	4.515E-03	
Ra-226	Rn-222+D	1.000E+00	2.276E-01	2.297E-01	
Ra-226	Pb-210	1.000E+00	1.357E-04	4.050E-04	
Ra-226	Bi-210	1.000E+00	4.717E-07	1.442E-06	
Ra-226	Po-210	1.000E+00	7.873E-05	3.923E-04	
Ra-226	∑DSR(j)		2.324E-01	2.350E-01	
Rn-222+D	Rn-222+D	1.000E+00	5.570E-03	1.917E-34	
Rn-222+D	Pb-210	1.000E+00	4.111E-06	4.040E-06	
Rn-222+D	Bi-210	1.000E+00	1.471E-08	1.456E-08	
Rn-222+D	Po-210	1.000E+00	3.244E-06	5.554E-06	
Rn-222+D	∑DSR(j)		5.577E-03	9.609E-06	
Th-230	Th-230	1.000E+00	8.349E-03	8.348E-03	
Th-230	Ra-226	1.000E+00	9.929E-07	2.962E-06	
Th-230	Rn-222+D	1.000E+00	4.914E-05	1.493E-04	
Th-230	Pb-210	1.000E+00	1.941E-08	1.370E-07	
Th-230	Bi-210	1.000E+00	6.631E-11	4.825E-10	
Th-230	Po-210	1.000E+00	8.953E-09	1.059E-07	
Th-230	∑DSR(j)		8.399E-03	8.501E-03	
Th-234+D	Th-234+D	1.000E+00	2.217E-04	6.073E-09	
Th-234+D	U-234	1.000E+00	2.896E-10	3.148E-10	
Th-234+D	Th-230	1.000E+00	8.348E-15	2.812E-14	
Th-234+D	Ra-226	1.000E+00	6.123E-19	4.927E-18	
Th-234+D	Rn-222+D	1.000E+00	2.979E-17	2.460E-16	
Th-234+D	Pb-210	1.000E+00	8.218E-21	1.490E-19	
Th-234+D	Bi-210	1.000E+00	2.745E-23	5.184E-22	
Th-234+D	Po-210	1.000E+00	2.959E-21	9.441E-20	
Th-234+D	∑DSR(j)		2.217E-04	6.388E-09	

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
U-234	U-234	1.000E+00	1.185E-03	1.164E-03	
U-234	Th-230	1.000E+00	3.736E-08	1.112E-07	
U-234	Ra-226	1.000E+00	2.970E-12	2.060E-11	
U-234	Rn-222+D	1.000E+00	1.450E-10	1.030E-09	
U-234	Pb-210	1.000E+00	4.307E-14	6.550E-13	
U-234	Bi-210	1.000E+00	1.446E-16	2.283E-15	
U-234	Po-210	1.000E+00	1.645E-14	4.274E-13	
U-234	∑DSR(j)		1.185E-03	1.165E-03	
U-238	U-238	5.400E-05	5.694E-08	5.594E-08	
U-238	U-238	9.999E-01	1.054E-03	1.036E-03	
U-238	Th-234+D	9.999E-01	2.088E-03	2.269E-03	
U-238	U-234	9.999E-01	1.388E-09	4.640E-09	
U-238	Th-230	9.999E-01	2.689E-14	2.161E-13	
U-238	Ra-226	9.999E-01	1.491E-18	2.630E-17	
U-238	Rn-222+D	9.999E-01	7.152E-17	1.302E-15	
U-238	Pb-210	9.999E-01	1.590E-20	6.133E-19	
U-238	Bi-210	9.999E-01	5.219E-23	2.114E-21	
U-238	Po-210	9.999E-01	4.877E-21	3.383E-19	
U-238	∑DSR(j)		3.142E-03	3.305E-03	

The DSR includes contributions from associated (half-life ≤ 1 day) daughters.

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00
Bi-210	1.036E+05	6.705E+05
Pb-210	1.424E+03	1.116E+03
Po-210	3.289E+03	2.237E+04
Ra-226	1.076E+02	1.064E+02
Rn-222	4.482E+03	2.602E+06
Th-230	2.977E+03	2.941E+03
Th-234	1.128E+05	3.914E+09
U-234	2.109E+04	2.147E+04
U-238	7.956E+03	7.564E+03

Summary : Road Construction Worker - PG in Road Base with Shield (Center)
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Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Nuclide (i)	Initial (pCi/g)	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
Bi-210	1.350E+01	0.000E+00	2.413E-04	1.036E+05	2.413E-04	1.036E+05
Pb-210	1.350E+01	1.000E+00	2.241E-02	1.116E+03	1.755E-02	1.424E+03
Po-210	1.350E+01	0.000E+00	7.600E-03	3.289E+03	7.600E-03	3.289E+03
Ra-226	1.350E+01	0.0872 ± 0.0002	2.372E-01	1.054E+02	2.324E-01	1.076E+02
Rn-222	1.350E+01	0.000E+00	5.577E-03	4.482E+03	5.577E-03	4.482E+03
Th-230	2.500E+00	1.000E+00	8.501E-03	2.941E+03	8.399E-03	2.977E+03
Th-234	1.500E+00	0.000E+00	2.217E-04	1.128E+05	2.217E-04	1.128E+05
U-234	1.600E+00	0.000E+00	1.185E-03	2.109E+04	1.185E-03	2.109E+04
U-238	1.500E+00	0.3393 ± 0.0007	3.338E-03	7.490E+03	3.142E-03	7.956E+03

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.270E-05	0.000E+00
Bi-210	Pb-210	1.000E+00	4.652E-04	4.579E-04
Bi-210	Ra-226	1.000E+00	6.368E-06	1.946E-05
Bi-210	Rn-222	1.000E+00	1.986E-07	1.966E-07
Bi-210	Th-230	1.000E+00	1.658E-10	1.206E-09
Bi-210	Th-234	1.000E+00	4.118E-23	7.776E-22
Bi-210	U-234	1.000E+00	2.314E-16	3.653E-15
Bi-210	U-238	9.999E-01	7.828E-23	3.171E-21
Bi-210	∑DOSE(j)		4.845E-04	4.775E-04
Po-210	Bi-210	1.000E+00	3.245E-03	5.034E-04
Po-210	Pb-210	1.000E+00	1.043E-01	1.750E-01
Po-210	Po-210	1.000E+00	1.026E-01	1.509E-02
Po-210	Ra-226	1.000E+00	1.063E-03	5.296E-03
Po-210	Rn-222	1.000E+00	4.379E-05	7.499E-05
Po-210	Th-230	1.000E+00	2.238E-08	2.648E-07
Po-210	Th-234	1.000E+00	4.439E-21	1.416E-19
Po-210	U-234	1.000E+00	2.632E-14	6.838E-13
Po-210	U-238	9.999E-01	7.316E-21	5.074E-19
Po-210	∑DOSE(j)		2.113E-01	1.960E-01
Pb-210	Pb-210	1.000E+00	1.322E-01	1.270E-01
Pb-210	Ra-226	1.000E+00	1.832E-03	5.467E-03
Pb-210	Rn-222	1.000E+00	5.550E-05	5.454E-05
Pb-210	Th-230	1.000E+00	4.853E-08	3.426E-07
Pb-210	Th-234	1.000E+00	1.233E-20	2.234E-19
Pb-210	U-234	1.000E+00	6.891E-14	1.048E-12
Pb-210	U-238	9.999E-01	2.384E-20	9.200E-19
Pb-210	∑DOSE(j)		1.341E-01	1.326E-01
Ra-226	Ra-226	1.000E+00	6.175E-02	6.095E-02
Ra-226	Th-230	1.000E+00	2.482E-06	7.404E-06
Ra-226	Th-234	1.000E+00	9.184E-19	7.391E-18
Ra-226	U-234	1.000E+00	4.751E-12	3.297E-11
Ra-226	U-238	9.999E-01	2.236E-18	3.945E-17
Ra-226	∑DOSE(j)		6.175E-02	6.095E-02
Rn-222	Ra-226	1.000E+00	3.073E+00	3.101E+00
Rn-222	Rn-222	1.000E+00	7.520E-02	0.000E+00
Rn-222	Th-230	1.000E+00	1.229E-04	3.732E-04
Rn-222	Th-234	1.000E+00	4.468E-17	3.690E-16
Rn-222	U-234	1.000E+00	2.320E-10	1.648E-09
Rn-222	U-238	9.999E-01	1.073E-16	1.953E-15
Rn-222	∑DOSE(j)		3.148E+00	3.101E+00
Th-230	Th-230	1.000E+00	2.087E-02	2.087E-02
Th-230	Th-234	1.000E+00	1.252E-14	4.218E-14
Th-230	U-234	1.000E+00	5.977E-08	1.779E-07
Th-230	U-238	9.999E-01	4.034E-14	3.242E-13
Th-230	∑DOSE(j)		2.087E-02	2.087E-02

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	3.325E-04	9.110E-09
Th-234	U-238	9.999E-01	3.132E-03	3.404E-03
Th-234	∑DOSE(j)		3.464E-03	3.404E-03
U-234	Th-234	1.000E+00	4.344E-10	4.722E-10
U-234	U-234	1.000E+00	1.896E-03	1.863E-03
U-234	U-238	9.999E-01	2.082E-09	6.959E-09
U-234	∑DOSE(j)		1.896E-03	1.863E-03
U-238	U-238	5.400E-05	8.541E-08	8.390E-08
U-238	U-238	9.999E-01	1.581E-03	1.554E-03
U-238	∑DOSE(j)		1.582E-03	1.554E-03

THF(i) is the thread fraction of the parent nuclide.

Summary : Road Construction Worker - PG in Road Base with Shield (Center)
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Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.350E+01	3.063E-24
Bi-210	Pb-210	1.000E+00	0.000E+00	1.155E+01
Bi-210	Ra-226	1.000E+00	0.000E+00	3.223E-01
Bi-210	Rn-222	1.000E+00	0.000E+00	4.960E-03
Bi-210	Th-230	1.000E+00	0.000E+00	1.264E-05
Bi-210	Th-234	1.000E+00	0.000E+00	4.515E-18
Bi-210	U-234	1.000E+00	0.000E+00	2.353E-11
Bi-210	U-238	9.999E-01	0.000E+00	1.067E-17
Bi-210	∑S(j):		1.350E+01	1.188E+01
Po-210	Bi-210	1.000E+00	0.000E+00	6.623E-02
Po-210	Pb-210	1.000E+00	0.000E+00	9.479E+00
Po-210	Po-210	1.000E+00	1.350E+01	1.985E+00
Po-210	Ra-226	1.000E+00	0.000E+00	1.689E-01
Po-210	Rn-222	1.000E+00	0.000E+00	4.049E-03
Po-210	Th-230	1.000E+00	0.000E+00	4.992E-06
Po-210	Th-234	1.000E+00	0.000E+00	1.366E-18
Po-210	U-234	1.000E+00	0.000E+00	7.521E-12
Po-210	U-238	9.999E-01	0.000E+00	2.722E-18
Po-210	∑S(j):		1.350E+01	1.170E+01
Pb-210	Pb-210	1.000E+00	1.350E+01	1.297E+01
Pb-210	Ra-226	1.000E+00	0.000E+00	3.685E-01
Pb-210	Rn-222	1.000E+00	0.000E+00	5.568E-03
Pb-210	Th-230	1.000E+00	0.000E+00	1.471E-05
Pb-210	Th-234	1.000E+00	0.000E+00	5.371E-18
Pb-210	U-234	1.000E+00	0.000E+00	2.786E-11
Pb-210	U-238	9.999E-01	0.000E+00	1.292E-17
Pb-210	∑S(j):		1.350E+01	1.335E+01
Ra-226	Ra-226	1.000E+00	1.350E+01	1.332E+01
Ra-226	Th-230	1.000E+00	0.000E+00	1.076E-03
Ra-226	Th-234	1.000E+00	0.000E+00	6.472E-16
Ra-226	U-234	1.000E+00	0.000E+00	3.088E-09
Ra-226	U-238	9.999E-01	0.000E+00	2.087E-15
Ra-226	∑S(j):		1.350E+01	1.333E+01
Rn-222	Ra-226	1.000E+00	0.000E+00	1.218E+01
Rn-222	Rn-222	1.000E+00	1.350E+01	4.647E-31
Rn-222	Th-230	1.000E+00	0.000E+00	9.699E-04
Rn-222	Th-234	1.000E+00	0.000E+00	5.740E-16
Rn-222	U-234	1.000E+00	0.000E+00	2.746E-09
Rn-222	U-238	9.999E-01	0.000E+00	1.825E-15
Rn-222	∑S(j):		1.350E+01	1.218E+01
Th-230	Th-230	1.000E+00	2.500E+00	2.500E+00
Th-230	Th-234	1.000E+00	0.000E+00	3.270E-12
Th-230	U-234	1.000E+00	0.000E+00	1.428E-05
Th-230	U-238	9.999E-01	0.000E+00	1.567E-11
Th-230	∑S(j):		2.500E+00	2.500E+00

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.500E+00	4.110E-05
Th-234	U-238	9.999E-01	0.000E+00	1.476E+00
Th-234	∑S(j):		1.500E+00	1.476E+00
U-234	Th-234	1.000E+00	0.000E+00	3.983E-07
U-234	U-234	1.000E+00	1.600E+00	1.572E+00
U-234	U-238	9.999E-01	0.000E+00	3.786E-06
U-234	∑S(j):		1.600E+00	1.572E+00
U-238	U-238	5.400E-05	8.100E-05	7.958E-05
U-238	U-238	9.999E-01	1.500E+00	1.474E+00
U-238	∑S(j):		1.500E+00	1.474E+00

THF(i) is the thread fraction of the parent nuclide.

RESCALC.EXE execution time = 23.56 seconds

RESRAD Modelling Results

Road Construction Worker – Road Base with Surface Shield_Edge

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Dose Conversion Factor (and Related) Parameter Summary
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
A-1	DCF's for external ground radiation, (mrem/yr)/(pCi/g)			
A-1	At-218 (Source: ICRP 60)	4.878E-03	4.878E-03	DCF1(1)
A-1	Bi-210 (Source: ICRP 60)	5.476E-03	5.476E-03	DCF1(2)
A-1	Bi-214 (Source: ICRP 60)	9.325E+00	9.325E+00	DCF1(3)
A-1	Pa-234 (Source: ICRP 60)	1.088E+01	1.088E+01	DCF1(4)
A-1	Pa-234m (Source: ICRP 60)	9.867E-02	9.867E-02	DCF1(5)
A-1	Pb-210 (Source: ICRP 60)	1.981E-03	1.981E-03	DCF1(6)
A-1	Pb-214 (Source: ICRP 60)	1.243E+00	1.243E+00	DCF1(7)
A-1	Po-210 (Source: ICRP 60)	4.934E-05	4.934E-05	DCF1(8)
A-1	Po-214 (Source: ICRP 60)	4.840E-04	4.840E-04	DCF1(9)
A-1	Po-218 (Source: ICRP 60)	5.326E-05	5.326E-05	DCF1(10)
A-1	Ra-226 (Source: ICRP 60)	2.915E-02	2.915E-02	DCF1(11)
A-1	Rn-222 (Source: ICRP 60)	2.186E-03	2.186E-03	DCF1(12)
A-1	Th-230 (Source: ICRP 60)	1.071E-03	1.071E-03	DCF1(13)
A-1	Th-234 (Source: ICRP 60)	2.130E-02	2.130E-02	DCF1(14)
A-1	Tl-210 (Source: ICRP 60)	1.661E+01	1.661E+01	DCF1(15)
A-1	U-234 (Source: ICRP 60)	3.439E-04	3.439E-04	DCF1(16)
A-1	U-238 (Source: ICRP 60)	7.961E-05	7.961E-05	DCF1(17)
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Bi-210	3.441E-04	3.441E-04	DCF2(1)
B-1	Pb-210	2.072E-02	2.072E-02	DCF2(2)
B-1	Po-210	1.591E-02	1.591E-02	DCF2(3)
B-1	Ra-226	3.515E-02	3.515E-02	DCF2(4)
B-1	Rn-222+D	1.073E-04	0.000E+00	DCF2(5)
B-1	Th-230	3.700E-01	3.700E-01	DCF2(6)
B-1	Th-234+D	2.849E-05	2.849E-05	DCF2(7)
B-1	U-234	3.478E-02	3.478E-02	DCF2(8)
B-1	U-238	2.960E-02	2.960E-02	DCF2(9)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Bi-210	4.810E-06	4.810E-06	DCF3(1)
D-1	Pb-210	2.553E-03	2.553E-03	DCF3(2)
D-1	Po-210	4.440E-03	4.440E-03	DCF3(3)
D-1	Ra-226	1.036E-03	1.036E-03	DCF3(4)
D-1	Rn-222+D	9.249E-07	0.000E+00	DCF3(5)
D-1	Th-230	7.770E-04	7.770E-04	DCF3(6)
D-1	Th-234+D	1.259E-05	1.258E-05	DCF3(7)
D-1	U-234	1.813E-04	1.813E-04	DCF3(8)
D-1	U-238	1.665E-04	1.665E-04	DCF3(9)
D-34	Food transfer factors:			
D-34	Bi-210 , plant/soil concentration ratio, dimensionless	1.000E-01	1.000E-01	RTF(1,1)
D-34	Bi-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(1,2)
D-34	Bi-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-04	5.000E-04	RTF(1,3)
D-34				
D-34	Pb-210 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(2,1)
D-34	Pb-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(2,2)
D-34	Pb-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(2,3)
D-34				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(3,1)
D-34	Po-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(3,2)
D-34	Po-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.400E-04	3.400E-04	RTF(3,3)
D-34				
D-34	Ra-226 , plant/soil concentration ratio, dimensionless	4.000E-02	4.000E-02	RTF(4,1)
D-34	Ra-226 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,2)
D-34	Ra-226 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,3)
D-34				
D-34	Rn-222+D , plant/soil concentration ratio, dimensionless	0.000E+00	0.000E+00	RTF(5,1)
D-34	Rn-222+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,2)
D-34	Rn-222+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,3)
D-34				
D-34	Th-230 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(6,1)
D-34	Th-230 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(6,2)
D-34	Th-230 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(6,3)
D-34				
D-34	Th-234+D , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(7,1)
D-34	Th-234+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(7,2)
D-34	Th-234+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	U-234 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(8,1)
D-34	U-234 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(8,2)
D-34	U-234 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(8,3)
D-34				
D-34	U-238 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(9,1)
D-34	U-238 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(9,2)
D-34	U-238 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(9,3)
D-5	Bioaccumulation factors, fresh water, L/kg:			
D-5	Bi-210 , fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Bi-210 , crustacea and mollusks	1.000E+01	1.000E+01	BIOFAC(1,2)
D-5				
D-5	Pb-210 , fish	3.000E+02	3.000E+02	BIOFAC(2,1)
D-5	Pb-210 , crustacea and mollusks	1.000E+02	1.000E+02	BIOFAC(2,2)
D-5				
D-5	Po-210 , fish	1.000E+02	1.000E+02	BIOFAC(3,1)
D-5	Po-210 , crustacea and mollusks	2.000E+04	2.000E+04	BIOFAC(3,2)
D-5				
D-5	Ra-226 , fish	5.000E+01	5.000E+01	BIOFAC(4,1)
D-5	Ra-226 , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(4,2)
D-5				
D-5	Rn-222+D , fish	0.000E+00	0.000E+00	BIOFAC(5,1)
D-5	Rn-222+D , crustacea and mollusks	0.000E+00	0.000E+00	BIOFAC(5,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(6,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(6,2)
D-5				
D-5	Th-234+D , fish	1.000E+02	1.000E+02	BIOFAC(7,1)
D-5	Th-234+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(7,2)
D-5				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-5	U-234 , fish	1.000E+01	1.000E+01	BIOFAC(8,1)
D-5	U-234 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(8,2)
D-5				
D-5	U-238 , fish	1.000E+01	1.000E+01	BIOFAC(9,1)
D-5	U-238 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(9,2)

#For DCF1(xxx) only, factors are for infinite depth & area. See ETFG table in Ground Pathway of Detailed Report.
*Base Case means Default.Lib w/o Associate Nuclide contributions.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.500E+03	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	2.500E-01	2.000E+00	---	THICK0
R011	Fraction of contamination that is submerged	0.000E+00	0.000E+00	---	SUBMFRACT
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	not used	3.000E+00	---	T(3)
R011	Times for calculations (yr)	not used	1.000E+01	---	T(4)
R011	Times for calculations (yr)	not used	3.000E+01	---	T(5)
R011	Times for calculations (yr)	not used	1.000E+02	---	T(6)
R011	Times for calculations (yr)	not used	3.000E+02	---	T(7)
R011	Times for calculations (yr)	not used	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Bi-210	1.350E+01	0.000E+00	---	S1(1)
R012	Initial principal radionuclide (pCi/g): Pb-210	1.350E+01	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Po-210	1.350E+01	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Ra-226	1.350E+01	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Rn-222	1.350E+01	0.000E+00	---	S1(5)
R012	Initial principal radionuclide (pCi/g): Th-230	2.500E+00	0.000E+00	---	S1(6)
R012	Initial principal radionuclide (pCi/g): Th-234	1.500E+00	0.000E+00	---	S1(7)
R012	Initial principal radionuclide (pCi/g): U-234	1.600E+00	0.000E+00	---	S1(8)
R012	Initial principal radionuclide (pCi/g): U-238	1.500E+00	0.000E+00	---	S1(9)
R012	Concentration in groundwater (pCi/L): Bi-210	not used	0.000E+00	---	W1(1)
R012	Concentration in groundwater (pCi/L): Pb-210	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Po-210	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Rn-222	not used	0.000E+00	---	W1(5)
R012	Concentration in groundwater (pCi/L): Th-230	not used	0.000E+00	---	W1(6)
R012	Concentration in groundwater (pCi/L): Th-234	not used	0.000E+00	---	W1(7)
R012	Concentration in groundwater (pCi/L): U-234	not used	0.000E+00	---	W1(8)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(9)
R013	Cover depth (m)	1.200E-01	0.000E+00	---	COVER0
R013	Density of cover material (g/cm**3)	2.250E+00	1.500E+00	---	DENSCV
R013	Cover depth erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCV
R013	Density of contaminated zone (g/cm**3)	2.250E+00	1.500E+00	---	DENSCZ
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCZ
R013	Contaminated zone total porosity	4.000E-01	4.000E-01	---	TPCZ
R013	Contaminated zone field capacity	2.000E-01	2.000E-01	---	FCCZ
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01	---	HCCZ
R013	Contaminated zone b parameter	5.300E+00	5.300E+00	---	BCZ
R013	Average annual wind speed (m/sec)	2.000E+00	2.000E+00	---	WIND
R013	Humidity in air (g/m**3)	not used	8.000E+00	---	HUMID
R013	Evapotranspiration coefficient	5.000E-01	5.000E-01	---	EVAPTR
R013	Precipitation (m/yr)	1.000E+00	1.000E+00	---	PRECIP
R013	Irrigation (m/yr)	2.000E-01	2.000E-01	---	RI
R013	Irrigation mode	overhead	overhead	---	IDITCH

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R013	Runoff coefficient	2.000E-01	2.000E-01	---	RUNOFF
R013	Watershed area for nearby stream or pond (m**2)	not used	1.000E+06	---	WAREA
R013	Accuracy for water/soil computations	not used	1.000E-03	---	EPS
R014	Density of saturated zone (g/cm**3)	not used	1.500E+00	---	DENSAQ
R014	Saturated zone total porosity	not used	4.000E-01	---	TPSZ
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Bi-210				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)
R016	Distribution coefficients for Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.876E-03	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(3)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(3,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(3)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.764E-02	ALEACH(3)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(3)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Ra-226				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(4)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(4,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(4)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.267E-02	ALEACH(4)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(4)
R016	Distribution coefficients for Rn-222				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(5)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(5,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(5)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(5)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(5)
R016	Distribution coefficients for Th-230				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(6)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(6,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(6)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(6)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(6)
R016	Distribution coefficients for Th-234				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(7)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(7,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(7)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(7)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(7)
R016	Distribution coefficients for U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(8)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(8,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(8)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(8)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(8)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R017	Inhalation rate (m**3/yr)	1.140E+04	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	2.000E-04	1.000E-04	---	MLINH
R017	Exposure duration	1.000E+00	3.000E+01	---	ED
R017	Shielding factor, inhalation	4.000E-01	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	7.000E-01	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	0.000E+00	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	2.300E-01	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	-1.000E+00	1.000E+00	-1 shows non-circular AREA.	FS

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	4.417E+00	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	8.833E+00	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	1.325E+01	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	1.767E+01	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	2.208E+01	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	2.650E+01	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	3.092E+01	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	3.533E+01	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	3.975E+01	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	4.417E+01	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	4.858E+01	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	5.300E+01	0.000E+00	---	RAD_SHAPE(12)
R017	Fractions of annular areas within AREA:				
R017	Ring 1	5.000E-01	1.000E+00	---	FRACA(1)
R017	Ring 2	5.000E-01	2.732E-01	---	FRACA(2)
R017	Ring 3	5.000E-01	0.000E+00	---	FRACA(3)
R017	Ring 4	4.400E-01	0.000E+00	---	FRACA(4)
R017	Ring 5	2.800E-01	0.000E+00	---	FRACA(5)
R017	Ring 6	2.200E-01	0.000E+00	---	FRACA(6)
R017	Ring 7	1.800E-01	0.000E+00	---	FRACA(7)
R017	Ring 8	1.500E-01	0.000E+00	---	FRACA(8)
R017	Ring 9	1.300E-01	0.000E+00	---	FRACA(9)
R017	Ring 10	1.200E-01	0.000E+00	---	FRACA(10)
R017	Ring 11	1.100E-01	0.000E+00	---	FRACA(11)
R017	Ring 12	4.600E-02	0.000E+00	---	FRACA(12)
R018	Fruits, vegetables and grain consumption (kg/yr)	not used	1.600E+02	---	DIET(1)
R018	Leafy vegetable consumption (kg/yr)	not used	1.400E+01	---	DIET(2)
R018	Milk consumption (L/yr)	not used	9.200E+01	---	DIET(3)
R018	Meat and poultry consumption (kg/yr)	not used	6.300E+01	---	DIET(4)
R018	Fish consumption (kg/yr)	not used	5.400E+00	---	DIET(5)
R018	Other seafood consumption (kg/yr)	not used	9.000E-01	---	DIET(6)
R018	Soil ingestion rate (g/yr)	8.250E+01	3.650E+01	---	SOIL
R018	Drinking water intake (L/yr)	not used	5.100E+02	---	DWI
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)
R19B	Translocation Factor for Fodder	not used	1.000E+00	---	TIV(3)
R19B	Dry Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RDRY(1)
R19B	Dry Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RDRY(2)
R19B	Dry Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RDRY(3)
R19B	Wet Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RWET(1)
R19B	Wet Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RWET(2)
R19B	Wet Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RWET(3)
R19B	Weathering Removal Constant for Vegetation	not used	2.000E+01	---	WLAM
C14	C-12 concentration in water (g/cm**3)	not used	2.000E-05	---	C12WTR
C14	C-12 concentration in contaminated soil (g/g)	not used	3.000E-02	---	C12CZ
C14	Fraction of vegetation carbon from soil	not used	2.000E-02	---	CSOIL
C14	Fraction of vegetation carbon from air	not used	9.800E-01	---	CAIR
C14	C-14 evasion layer thickness in soil (m)	not used	3.000E-01	---	DMC
C14	C-14 evasion flux rate from soil (1/sec)	not used	7.000E-07	---	EVSN
C14	C-12 evasion flux rate from soil (1/sec)	not used	1.000E-10	---	REVSN
C14	Fraction of grain in beef cattle feed	not used	8.000E-01	---	AVFG4
C14	Fraction of grain in milk cow feed	not used	2.000E-01	---	AVFG5
STOR	Storage times of contaminated foodstuffs (days):				
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS
TITL	Maximum number of integration points for dose	17	---	---	LYMAX
TITL	Maximum number of integration points for risk	257	---	---	KYMAX

Summary of Pathway Selections

Pathway	User Selection
1 -- external gamma	active
2 -- inhalation (w/o radon)	active
3 -- plant ingestion	suppressed
4 -- meat ingestion	suppressed
5 -- milk ingestion	suppressed
6 -- aquatic foods	suppressed
7 -- drinking water	suppressed
8 -- soil ingestion	active
9 -- radon	suppressed
Find peak pathway doses	suppressed

Summary : Case No. 8: Construction Worker - PG in Road Base with Shield (Edge)
File : C:\USERS\NEMICKASH\DESKTOP\FERTILIZER INSTITUTE\RESRAD\RCW_RBSS_EDGE_070319.RAD

Contaminated Zone Dimensions	
Area:	1500.00 square meters
Thickness:	0.25 meters
Cover Depth:	0.12 meters

Initial Soil Concentrations, pCi/g	
Bi-210	1.350E+01
Pb-210	1.350E+01
Po-210	1.350E+01
Ra-226	1.350E+01
Rn-222	1.350E+01
Th-230	2.500E+00
Th-234	1.500E+00
U-234	1.600E+00
U-238	1.500E+00

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 2.500E+01 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0.000E+00	1.000E+00
TDOSE(t):	2.007E+00	1.966E+00
M(t):	8.028E-02	7.863E-02

Maximum TDOSE(t): 2.007E+00 mrem/yr at t = 0.000E+00 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	2.786E-06	0.0000	4.567E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.206E-03	0.0016
Pb-210	1.016E-04	0.0001	5.476E-03	0.0027	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.313E-01	0.1152
Po-210	2.906E-06	0.0000	1.394E-03	0.0007	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.012E-01	0.0504
Ra-226	1.538E+00	0.7662	6.968E-03	0.0035	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.560E-02	0.0277
Rn-222	3.761E-02	0.0187	2.759E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.813E-05	0.0000
Th-230	6.320E-05	0.0000	1.350E-02	0.0067	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.374E-03	0.0037
Th-234	1.629E-04	0.0001	5.961E-08	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.827E-06	0.0000
U-234	2.311E-07	0.0000	8.048E-04	0.0004	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.091E-03	0.0005
U-238	1.534E-03	0.0008	6.427E-04	0.0003	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.004E-03	0.0005
Total	1.577E+00	0.7859	2.883E-02	0.0144	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.009E-01	0.1997

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.255E-03	0.0016
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.369E-01	0.1180
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.026E-01	0.0511
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.600E+00	0.7974
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.771E-02	0.0188
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.093E-02	0.0104
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.698E-04	0.0001
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.896E-03	0.0009
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.181E-03	0.0016
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.007E+00	1.0000

*Sum of all water independent and dependent pathways.

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	1.426E-08	0.0000	6.840E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.965E-04	0.0003
Pb-210	1.021E-04	0.0001	6.280E-03	0.0032	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.961E-01	0.1506
Po-210	4.273E-07	0.0000	2.050E-04	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.488E-02	0.0076
Ra-226	1.552E+00	0.7894	7.048E-03	0.0036	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.262E-02	0.0319
Rn-222	4.381E-08	0.0000	2.694E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.269E-04	0.0001
Th-230	1.885E-04	0.0001	1.350E-02	0.0069	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.378E-03	0.0038
Th-234	4.464E-09	0.0000	2.020E-10	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.587E-10	0.0000
U-234	2.278E-07	0.0000	7.908E-04	0.0004	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.072E-03	0.0005
U-238	1.668E-03	0.0008	6.315E-04	0.0003	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.928E-04	0.0005
Total	1.554E+00	0.7904	2.846E-02	0.0145	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.836E-01	0.1951

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.034E-04	0.0003
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.024E-01	0.1538
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.508E-02	0.0077
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.621E+00	0.8248
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.297E-04	0.0001
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.106E-02	0.0107
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.124E-09	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.863E-03	0.0009
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.292E-03	0.0017
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.966E+00	1.0000

*Sum of all water independent and dependent pathways.

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
Bi-210	Bi-210	1.000E+00	7.412E-07	1.682E-31	
Bi-210	Po-210	1.000E+00	2.403E-04	3.729E-05	
Bi-210	∑DSR(j)		2.411E-04	3.729E-05	
Pb-210	Pb-210	1.000E+00	9.794E-03	9.410E-03	
Pb-210	Bi-210	1.000E+00	2.715E-05	2.672E-05	
Pb-210	Po-210	1.000E+00	7.726E-03	1.297E-02	
Pb-210	∑DSR(j)		1.755E-02	2.240E-02	
Po-210	Po-210	1.000E+00	7.600E-03	1.117E-03	
Ra-226	Ra-226	1.000E+00	4.495E-03	4.436E-03	
Ra-226	Rn-222+D	1.000E+00	1.138E-01	1.149E-01	
Ra-226	Pb-210	1.000E+00	1.357E-04	4.050E-04	
Ra-226	Bi-210	1.000E+00	3.716E-07	1.136E-06	
Ra-226	Po-210	1.000E+00	7.873E-05	3.923E-04	
Ra-226	∑DSR(j)		1.185E-01	1.201E-01	
Rn-222+D	Rn-222+D	1.000E+00	2.786E-03	9.589E-35	
Rn-222+D	Pb-210	1.000E+00	4.111E-06	4.040E-06	
Rn-222+D	Bi-210	1.000E+00	1.159E-08	1.147E-08	
Rn-222+D	Po-210	1.000E+00	3.244E-06	5.554E-06	
Rn-222+D	∑DSR(j)		2.793E-03	9.605E-06	
Th-230	Th-230	1.000E+00	8.348E-03	8.348E-03	
Th-230	Ra-226	1.000E+00	9.757E-07	2.910E-06	
Th-230	Rn-222+D	1.000E+00	2.458E-05	7.466E-05	
Th-230	Pb-210	1.000E+00	1.941E-08	1.370E-07	
Th-230	Bi-210	1.000E+00	5.225E-11	3.802E-10	
Th-230	Po-210	1.000E+00	8.952E-09	1.059E-07	
Th-230	∑DSR(j)		8.374E-03	8.426E-03	
Th-234+D	Th-234+D	1.000E+00	1.132E-04	3.102E-09	
Th-234+D	U-234	1.000E+00	2.896E-10	3.147E-10	
Th-234+D	Th-230	1.000E+00	8.348E-15	2.812E-14	
Th-234+D	Ra-226	1.000E+00	6.017E-19	4.842E-18	
Th-234+D	Rn-222+D	1.000E+00	1.490E-17	1.230E-16	
Th-234+D	Pb-210	1.000E+00	8.218E-21	1.490E-19	
Th-234+D	Bi-210	1.000E+00	2.163E-23	4.084E-22	
Th-234+D	Po-210	1.000E+00	2.959E-21	9.441E-20	
Th-234+D	∑DSR(j)		1.132E-04	3.416E-09	

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00 (mrem/yr)/(pCi/g)
U-234	U-234	1.000E+00	1.185E-03	1.164E-03
U-234	Th-230	1.000E+00	3.735E-08	1.112E-07
U-234	Ra-226	1.000E+00	2.918E-12	2.025E-11
U-234	Rn-222+D	1.000E+00	7.251E-11	5.150E-10
U-234	Pb-210	1.000E+00	4.307E-14	6.550E-13
U-234	Bi-210	1.000E+00	1.140E-16	1.799E-15
U-234	Po-210	1.000E+00	1.645E-14	4.274E-13
U-234	∑DSR(j)		1.185E-03	1.164E-03
U-238	U-238	5.400E-05	5.694E-08	5.594E-08
U-238	U-238	9.999E-01	1.054E-03	1.036E-03
U-238	Th-234+D	9.999E-01	1.066E-03	1.159E-03
U-238	U-234	9.999E-01	1.388E-09	4.639E-09
U-238	Th-230	9.999E-01	2.689E-14	2.161E-13
U-238	Ra-226	9.999E-01	1.465E-18	2.584E-17
U-238	Rn-222+D	9.999E-01	3.577E-17	6.513E-16
U-238	Pb-210	9.999E-01	1.590E-20	6.133E-19
U-238	Bi-210	9.999E-01	4.112E-23	1.665E-21
U-238	Po-210	9.999E-01	4.877E-21	3.383E-19
U-238	∑DSR(j)		2.121E-03	2.195E-03

The DSR includes contributions from associated (half-life ≤ 1 day) daughters.

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00
Bi-210	1.037E+05	6.705E+05
Pb-210	1.425E+03	1.116E+03
Po-210	3.289E+03	2.237E+04
Ra-226	2.109E+02	2.081E+02
Rn-222	8.950E+03	2.603E+06
Th-230	2.986E+03	2.967E+03
Th-234	2.208E+05	7.318E+09
U-234	2.109E+04	2.147E+04
U-238	1.179E+04	1.139E+04

Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Nuclide (i)	Initial (pCi/g)	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
Bi-210	1.350E+01	0.000E+00	2.411E-04	1.037E+05	2.411E-04	1.037E+05
Pb-210	1.350E+01	1.000E+00	2.240E-02	1.116E+03	1.755E-02	1.425E+03
Po-210	1.350E+01	0.000E+00	7.600E-03	3.289E+03	7.600E-03	3.289E+03
Ra-226	1.350E+01	0.0900 ± 0.0002	1.210E-01	2.066E+02	1.185E-01	2.109E+02
Rn-222	1.350E+01	0.000E+00	2.793E-03	8.950E+03	2.793E-03	8.950E+03
Th-230	2.500E+00	1.000E+00	8.426E-03	2.967E+03	8.374E-03	2.986E+03
Th-234	1.500E+00	0.000E+00	1.132E-04	2.208E+05	1.132E-04	2.208E+05
U-234	1.600E+00	0.000E+00	1.185E-03	2.109E+04	1.185E-03	2.109E+04
U-238	1.500E+00	0.3128 ± 0.0006	2.217E-03	1.127E+04	2.121E-03	1.179E+04

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.001E-05	0.000E+00
Bi-210	Pb-210	1.000E+00	3.665E-04	3.607E-04
Bi-210	Ra-226	1.000E+00	5.017E-06	1.534E-05
Bi-210	Rn-222	1.000E+00	1.564E-07	1.549E-07
Bi-210	Th-230	1.000E+00	1.306E-10	9.504E-10
Bi-210	Th-234	1.000E+00	3.244E-23	6.126E-22
Bi-210	U-234	1.000E+00	1.823E-16	2.878E-15
Bi-210	U-238	9.999E-01	6.167E-23	2.498E-21
Bi-210	∑DOSE(j)		3.817E-04	3.762E-04
Po-210	Bi-210	1.000E+00	3.245E-03	5.034E-04
Po-210	Pb-210	1.000E+00	1.043E-01	1.750E-01
Po-210	Po-210	1.000E+00	1.026E-01	1.508E-02
Po-210	Ra-226	1.000E+00	1.063E-03	5.296E-03
Po-210	Rn-222	1.000E+00	4.379E-05	7.498E-05
Po-210	Th-230	1.000E+00	2.238E-08	2.648E-07
Po-210	Th-234	1.000E+00	4.439E-21	1.416E-19
Po-210	U-234	1.000E+00	2.632E-14	6.838E-13
Po-210	U-238	9.999E-01	7.315E-21	5.074E-19
Po-210	∑DOSE(j)		2.113E-01	1.960E-01
Pb-210	Pb-210	1.000E+00	1.322E-01	1.270E-01
Pb-210	Ra-226	1.000E+00	1.832E-03	5.467E-03
Pb-210	Rn-222	1.000E+00	5.550E-05	5.454E-05
Pb-210	Th-230	1.000E+00	4.853E-08	3.426E-07
Pb-210	Th-234	1.000E+00	1.233E-20	2.234E-19
Pb-210	U-234	1.000E+00	6.891E-14	1.048E-12
Pb-210	U-238	9.999E-01	2.384E-20	9.200E-19
Pb-210	∑DOSE(j)		1.341E-01	1.326E-01
Ra-226	Ra-226	1.000E+00	6.068E-02	5.989E-02
Ra-226	Th-230	1.000E+00	2.439E-06	7.276E-06
Ra-226	Th-234	1.000E+00	9.025E-19	7.262E-18
Ra-226	U-234	1.000E+00	4.669E-12	3.240E-11
Ra-226	U-238	9.999E-01	2.197E-18	3.876E-17
Ra-226	∑DOSE(j)		6.068E-02	5.990E-02
Rn-222	Ra-226	1.000E+00	1.537E+00	1.551E+00
Rn-222	Rn-222	1.000E+00	3.761E-02	0.000E+00
Rn-222	Th-230	1.000E+00	6.145E-05	1.866E-04
Rn-222	Th-234	1.000E+00	2.235E-17	1.845E-16
Rn-222	U-234	1.000E+00	1.160E-10	8.241E-10
Rn-222	U-238	9.999E-01	5.365E-17	9.770E-16
Rn-222	∑DOSE(j)		1.575E+00	1.551E+00
Th-230	Th-230	1.000E+00	2.087E-02	2.087E-02
Th-230	Th-234	1.000E+00	1.252E-14	4.218E-14
Th-230	U-234	1.000E+00	5.976E-08	1.779E-07
Th-230	U-238	9.999E-01	4.033E-14	3.242E-13
Th-230	∑DOSE(j)		2.087E-02	2.087E-02

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.698E-04	4.652E-09
Th-234	U-238	9.999E-01	1.599E-03	1.738E-03
Th-234	∑DOSE(j)		1.769E-03	1.738E-03
U-234	Th-234	1.000E+00	4.343E-10	4.721E-10
U-234	U-234	1.000E+00	1.896E-03	1.863E-03
U-234	U-238	9.999E-01	2.081E-09	6.959E-09
U-234	∑DOSE(j)		1.896E-03	1.863E-03
U-238	U-238	5.400E-05	8.541E-08	8.390E-08
U-238	U-238	9.999E-01	1.581E-03	1.554E-03
U-238	∑DOSE(j)		1.582E-03	1.554E-03

THF(i) is the thread fraction of the parent nuclide.

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.350E+01	3.063E-24
Bi-210	Pb-210	1.000E+00	0.000E+00	1.155E+01
Bi-210	Ra-226	1.000E+00	0.000E+00	3.223E-01
Bi-210	Rn-222	1.000E+00	0.000E+00	4.960E-03
Bi-210	Th-230	1.000E+00	0.000E+00	1.264E-05
Bi-210	Th-234	1.000E+00	0.000E+00	4.515E-18
Bi-210	U-234	1.000E+00	0.000E+00	2.353E-11
Bi-210	U-238	9.999E-01	0.000E+00	1.067E-17
Bi-210	∑S(j):		1.350E+01	1.188E+01
Po-210	Bi-210	1.000E+00	0.000E+00	6.623E-02
Po-210	Pb-210	1.000E+00	0.000E+00	9.479E+00
Po-210	Po-210	1.000E+00	1.350E+01	1.985E+00
Po-210	Ra-226	1.000E+00	0.000E+00	1.689E-01
Po-210	Rn-222	1.000E+00	0.000E+00	4.049E-03
Po-210	Th-230	1.000E+00	0.000E+00	4.992E-06
Po-210	Th-234	1.000E+00	0.000E+00	1.366E-18
Po-210	U-234	1.000E+00	0.000E+00	7.521E-12
Po-210	U-238	9.999E-01	0.000E+00	2.722E-18
Po-210	∑S(j):		1.350E+01	1.170E+01
Pb-210	Pb-210	1.000E+00	1.350E+01	1.297E+01
Pb-210	Ra-226	1.000E+00	0.000E+00	3.685E-01
Pb-210	Rn-222	1.000E+00	0.000E+00	5.568E-03
Pb-210	Th-230	1.000E+00	0.000E+00	1.471E-05
Pb-210	Th-234	1.000E+00	0.000E+00	5.371E-18
Pb-210	U-234	1.000E+00	0.000E+00	2.786E-11
Pb-210	U-238	9.999E-01	0.000E+00	1.292E-17
Pb-210	∑S(j):		1.350E+01	1.335E+01
Ra-226	Ra-226	1.000E+00	1.350E+01	1.332E+01
Ra-226	Th-230	1.000E+00	0.000E+00	1.076E-03
Ra-226	Th-234	1.000E+00	0.000E+00	6.472E-16
Ra-226	U-234	1.000E+00	0.000E+00	3.088E-09
Ra-226	U-238	9.999E-01	0.000E+00	2.087E-15
Ra-226	∑S(j):		1.350E+01	1.333E+01
Rn-222	Ra-226	1.000E+00	0.000E+00	1.218E+01
Rn-222	Rn-222	1.000E+00	1.350E+01	4.647E-31
Rn-222	Th-230	1.000E+00	0.000E+00	9.699E-04
Rn-222	Th-234	1.000E+00	0.000E+00	5.740E-16
Rn-222	U-234	1.000E+00	0.000E+00	2.746E-09
Rn-222	U-238	9.999E-01	0.000E+00	1.825E-15
Rn-222	∑S(j):		1.350E+01	1.218E+01
Th-230	Th-230	1.000E+00	2.500E+00	2.500E+00
Th-230	Th-234	1.000E+00	0.000E+00	3.270E-12
Th-230	U-234	1.000E+00	0.000E+00	1.428E-05
Th-230	U-238	9.999E-01	0.000E+00	1.567E-11
Th-230	∑S(j):		2.500E+00	2.500E+00

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.500E+00	4.110E-05
Th-234	U-238	9.999E-01	0.000E+00	1.476E+00
Th-234	∑S(j):		1.500E+00	1.476E+00
U-234	Th-234	1.000E+00	0.000E+00	3.983E-07
U-234	U-234	1.000E+00	1.600E+00	1.572E+00
U-234	U-238	9.999E-01	0.000E+00	3.786E-06
U-234	∑S(j):		1.600E+00	1.572E+00
U-238	U-238	5.400E-05	8.100E-05	7.958E-05
U-238	U-238	9.999E-01	1.500E+00	1.474E+00
U-238	∑S(j):		1.500E+00	1.474E+00

THF(i) is the thread fraction of the parent nuclide.

RESCALC.EXE execution time = 28.90 seconds

RESRAD Modelling Results

Road Construction Worker – Road Surface_Center

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Dose Conversion Factor (and Related) Parameter Summary
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
A-1	DCF's for external ground radiation, (mrem/yr)/(pCi/g)			
A-1	At-218 (Source: ICRP 60)	4.878E-03	4.878E-03	DCF1(1)
A-1	Bi-210 (Source: ICRP 60)	5.476E-03	5.476E-03	DCF1(2)
A-1	Bi-214 (Source: ICRP 60)	9.325E+00	9.325E+00	DCF1(3)
A-1	Pa-234 (Source: ICRP 60)	1.088E+01	1.088E+01	DCF1(4)
A-1	Pa-234m (Source: ICRP 60)	9.867E-02	9.867E-02	DCF1(5)
A-1	Pb-210 (Source: ICRP 60)	1.981E-03	1.981E-03	DCF1(6)
A-1	Pb-214 (Source: ICRP 60)	1.243E+00	1.243E+00	DCF1(7)
A-1	Po-210 (Source: ICRP 60)	4.934E-05	4.934E-05	DCF1(8)
A-1	Po-214 (Source: ICRP 60)	4.840E-04	4.840E-04	DCF1(9)
A-1	Po-218 (Source: ICRP 60)	5.326E-05	5.326E-05	DCF1(10)
A-1	Ra-226 (Source: ICRP 60)	2.915E-02	2.915E-02	DCF1(11)
A-1	Rn-222 (Source: ICRP 60)	2.186E-03	2.186E-03	DCF1(12)
A-1	Th-230 (Source: ICRP 60)	1.071E-03	1.071E-03	DCF1(13)
A-1	Th-234 (Source: ICRP 60)	2.130E-02	2.130E-02	DCF1(14)
A-1	Tl-210 (Source: ICRP 60)	1.661E+01	1.661E+01	DCF1(15)
A-1	U-234 (Source: ICRP 60)	3.439E-04	3.439E-04	DCF1(16)
A-1	U-238 (Source: ICRP 60)	7.961E-05	7.961E-05	DCF1(17)
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Bi-210	3.441E-04	3.441E-04	DCF2(1)
B-1	Pb-210	2.072E-02	2.072E-02	DCF2(2)
B-1	Po-210	1.591E-02	1.591E-02	DCF2(3)
B-1	Ra-226	3.515E-02	3.515E-02	DCF2(4)
B-1	Rn-222+D	1.073E-04	0.000E+00	DCF2(5)
B-1	Th-230	3.700E-01	3.700E-01	DCF2(6)
B-1	Th-234+D	2.849E-05	2.849E-05	DCF2(7)
B-1	U-234	3.478E-02	3.478E-02	DCF2(8)
B-1	U-238	2.960E-02	2.960E-02	DCF2(9)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Bi-210	4.810E-06	4.810E-06	DCF3(1)
D-1	Pb-210	2.553E-03	2.553E-03	DCF3(2)
D-1	Po-210	4.440E-03	4.440E-03	DCF3(3)
D-1	Ra-226	1.036E-03	1.036E-03	DCF3(4)
D-1	Rn-222+D	9.249E-07	0.000E+00	DCF3(5)
D-1	Th-230	7.770E-04	7.770E-04	DCF3(6)
D-1	Th-234+D	1.259E-05	1.258E-05	DCF3(7)
D-1	U-234	1.813E-04	1.813E-04	DCF3(8)
D-1	U-238	1.665E-04	1.665E-04	DCF3(9)
D-34	Food transfer factors:			
D-34	Bi-210 , plant/soil concentration ratio, dimensionless	1.000E-01	1.000E-01	RTF(1,1)
D-34	Bi-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(1,2)
D-34	Bi-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-04	5.000E-04	RTF(1,3)
D-34				
D-34	Pb-210 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(2,1)
D-34	Pb-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(2,2)
D-34	Pb-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(2,3)
D-34				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(3,1)
D-34	Po-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(3,2)
D-34	Po-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.400E-04	3.400E-04	RTF(3,3)
D-34				
D-34	Ra-226 , plant/soil concentration ratio, dimensionless	4.000E-02	4.000E-02	RTF(4,1)
D-34	Ra-226 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,2)
D-34	Ra-226 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,3)
D-34				
D-34	Rn-222+D , plant/soil concentration ratio, dimensionless	0.000E+00	0.000E+00	RTF(5,1)
D-34	Rn-222+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,2)
D-34	Rn-222+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,3)
D-34				
D-34	Th-230 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(6,1)
D-34	Th-230 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(6,2)
D-34	Th-230 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(6,3)
D-34				
D-34	Th-234+D , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(7,1)
D-34	Th-234+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(7,2)
D-34	Th-234+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	U-234 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(8,1)
D-34	U-234 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(8,2)
D-34	U-234 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(8,3)
D-34				
D-34	U-238 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(9,1)
D-34	U-238 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(9,2)
D-34	U-238 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(9,3)
D-5	Bioaccumulation factors, fresh water, L/kg:			
D-5	Bi-210 , fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Bi-210 , crustacea and mollusks	1.000E+01	1.000E+01	BIOFAC(1,2)
D-5				
D-5	Pb-210 , fish	3.000E+02	3.000E+02	BIOFAC(2,1)
D-5	Pb-210 , crustacea and mollusks	1.000E+02	1.000E+02	BIOFAC(2,2)
D-5				
D-5	Po-210 , fish	1.000E+02	1.000E+02	BIOFAC(3,1)
D-5	Po-210 , crustacea and mollusks	2.000E+04	2.000E+04	BIOFAC(3,2)
D-5				
D-5	Ra-226 , fish	5.000E+01	5.000E+01	BIOFAC(4,1)
D-5	Ra-226 , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(4,2)
D-5				
D-5	Rn-222+D , fish	0.000E+00	0.000E+00	BIOFAC(5,1)
D-5	Rn-222+D , crustacea and mollusks	0.000E+00	0.000E+00	BIOFAC(5,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(6,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(6,2)
D-5				
D-5	Th-234+D , fish	1.000E+02	1.000E+02	BIOFAC(7,1)
D-5	Th-234+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(7,2)
D-5				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-5	U-234 , fish	1.000E+01	1.000E+01	BIOFAC(8,1)
D-5	U-234 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(8,2)
D-5				
D-5	U-238 , fish	1.000E+01	1.000E+01	BIOFAC(9,1)
D-5	U-238 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(9,2)

#For DCF1(xxx) only, factors are for infinite depth & area. See ETFG table in Ground Pathway of Detailed Report.
*Base Case means Default.Lib w/o Associate Nuclide contributions.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.500E+03	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	1.200E-01	2.000E+00	---	THICK0
R011	Fraction of contamination that is submerged	0.000E+00	0.000E+00	---	SUBMFRACT
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	not used	3.000E+00	---	T(3)
R011	Times for calculations (yr)	not used	1.000E+01	---	T(4)
R011	Times for calculations (yr)	not used	3.000E+01	---	T(5)
R011	Times for calculations (yr)	not used	1.000E+02	---	T(6)
R011	Times for calculations (yr)	not used	3.000E+02	---	T(7)
R011	Times for calculations (yr)	not used	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Bi-210	6.100E-01	0.000E+00	---	S1(1)
R012	Initial principal radionuclide (pCi/g): Pb-210	6.100E-01	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Po-210	6.100E-01	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Ra-226	6.100E-01	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Rn-222	6.100E-01	0.000E+00	---	S1(5)
R012	Initial principal radionuclide (pCi/g): Th-230	1.100E-01	0.000E+00	---	S1(6)
R012	Initial principal radionuclide (pCi/g): Th-234	7.000E-02	0.000E+00	---	S1(7)
R012	Initial principal radionuclide (pCi/g): U-234	7.000E-02	0.000E+00	---	S1(8)
R012	Initial principal radionuclide (pCi/g): U-238	7.000E-02	0.000E+00	---	S1(9)
R012	Concentration in groundwater (pCi/L): Bi-210	not used	0.000E+00	---	W1(1)
R012	Concentration in groundwater (pCi/L): Pb-210	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Po-210	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Rn-222	not used	0.000E+00	---	W1(5)
R012	Concentration in groundwater (pCi/L): Th-230	not used	0.000E+00	---	W1(6)
R012	Concentration in groundwater (pCi/L): Th-234	not used	0.000E+00	---	W1(7)
R012	Concentration in groundwater (pCi/L): U-234	not used	0.000E+00	---	W1(8)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(9)
R013	Cover depth (m)	0.000E+00	0.000E+00	---	COVER0
R013	Density of cover material (g/cm**3)	not used	1.500E+00	---	DENSCV
R013	Cover depth erosion rate (m/yr)	not used	1.000E-03	---	VCV
R013	Density of contaminated zone (g/cm**3)	2.250E+00	1.500E+00	---	DENSCZ
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCZ
R013	Contaminated zone total porosity	4.000E-01	4.000E-01	---	TPCZ
R013	Contaminated zone field capacity	2.000E-01	2.000E-01	---	FCCZ
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01	---	HCCZ
R013	Contaminated zone b parameter	5.300E+00	5.300E+00	---	BCZ
R013	Average annual wind speed (m/sec)	2.000E+00	2.000E+00	---	WIND
R013	Humidity in air (g/m**3)	not used	8.000E+00	---	HUMID
R013	Evapotranspiration coefficient	5.000E-01	5.000E-01	---	EVAPTR
R013	Precipitation (m/yr)	1.000E+00	1.000E+00	---	PRECIP
R013	Irrigation (m/yr)	2.000E-01	2.000E-01	---	RI
R013	Irrigation mode	overhead	overhead	---	IDITCH

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R013	Runoff coefficient	2.000E-01	2.000E-01	---	RUNOFF
R013	Watershed area for nearby stream or pond (m**2)	not used	1.000E+06	---	WAREA
R013	Accuracy for water/soil computations	not used	1.000E-03	---	EPS
R014	Density of saturated zone (g/cm**3)	not used	1.500E+00	---	DENSAQ
R014	Saturated zone total porosity	not used	4.000E-01	---	TPSZ
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Bi-210				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.298E+01	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)
R016	Distribution coefficients for Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.849E-02	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(3)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(3,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(3)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.826E-01	ALEACH(3)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(3)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Ra-226				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(4)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(4,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(4)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	2.640E-02	ALEACH(4)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(4)
R016	Distribution coefficients for Rn-222				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(5)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(5,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(5)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.298E+01	ALEACH(5)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(5)
R016	Distribution coefficients for Th-230				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(6)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(6,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(6)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.086E-05	ALEACH(6)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(6)
R016	Distribution coefficients for Th-234				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(7)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(7,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(7)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.086E-05	ALEACH(7)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(7)
R016	Distribution coefficients for U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(8)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(8,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(8)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.693E-02	ALEACH(8)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(8)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.693E-02	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R017	Inhalation rate (m**3/yr)	1.140E+04	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	2.000E-04	1.000E-04	---	MLINH
R017	Exposure duration	1.000E+00	3.000E+01	---	ED
R017	Shielding factor, inhalation	4.000E-01	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	7.000E-01	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	0.000E+00	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	2.300E-01	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	-1.000E+00	1.000E+00	-1 shows non-circular AREA.	FS

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	4.250E+00	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	8.500E+00	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	1.275E+01	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	1.700E+01	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	2.125E+01	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	2.550E+01	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	2.975E+01	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	3.400E+01	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	3.825E+01	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	4.250E+01	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	4.675E+01	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	5.100E+01	0.000E+00	---	RAD_SHAPE(12)
R017	Fractions of annular areas within AREA:				
R017	Ring 1	1.000E+00	1.000E+00	---	FRACA(1)
R017	Ring 2	1.000E+00	2.732E-01	---	FRACA(2)
R017	Ring 3	5.000E-01	0.000E+00	---	FRACA(3)
R017	Ring 4	3.500E-01	0.000E+00	---	FRACA(4)
R017	Ring 5	2.600E-01	0.000E+00	---	FRACA(5)
R017	Ring 6	2.100E-01	0.000E+00	---	FRACA(6)
R017	Ring 7	1.800E-01	0.000E+00	---	FRACA(7)
R017	Ring 8	1.600E-01	0.000E+00	---	FRACA(8)
R017	Ring 9	1.400E-01	0.000E+00	---	FRACA(9)
R017	Ring 10	1.200E-01	0.000E+00	---	FRACA(10)
R017	Ring 11	1.100E-01	0.000E+00	---	FRACA(11)
R017	Ring 12	7.000E-02	0.000E+00	---	FRACA(12)
R018	Fruits, vegetables and grain consumption (kg/yr)	not used	1.600E+02	---	DIET(1)
R018	Leafy vegetable consumption (kg/yr)	not used	1.400E+01	---	DIET(2)
R018	Milk consumption (L/yr)	not used	9.200E+01	---	DIET(3)
R018	Meat and poultry consumption (kg/yr)	not used	6.300E+01	---	DIET(4)
R018	Fish consumption (kg/yr)	not used	5.400E+00	---	DIET(5)
R018	Other seafood consumption (kg/yr)	not used	9.000E-01	---	DIET(6)
R018	Soil ingestion rate (g/yr)	8.250E+01	3.650E+01	---	SOIL
R018	Drinking water intake (L/yr)	not used	5.100E+02	---	DWI
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)
R19B	Translocation Factor for Fodder	not used	1.000E+00	---	TIV(3)
R19B	Dry Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RDRY(1)
R19B	Dry Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RDRY(2)
R19B	Dry Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RDRY(3)
R19B	Wet Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RWET(1)
R19B	Wet Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RWET(2)
R19B	Wet Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RWET(3)
R19B	Weathering Removal Constant for Vegetation	not used	2.000E+01	---	WLAM
C14	C-12 concentration in water (g/cm**3)	not used	2.000E-05	---	C12WTR
C14	C-12 concentration in contaminated soil (g/g)	not used	3.000E-02	---	C12CZ
C14	Fraction of vegetation carbon from soil	not used	2.000E-02	---	CSOIL
C14	Fraction of vegetation carbon from air	not used	9.800E-01	---	CAIR
C14	C-14 evasion layer thickness in soil (m)	not used	3.000E-01	---	DMC
C14	C-14 evasion flux rate from soil (1/sec)	not used	7.000E-07	---	EVSN
C14	C-12 evasion flux rate from soil (1/sec)	not used	1.000E-10	---	REVSN
C14	Fraction of grain in beef cattle feed	not used	8.000E-01	---	AVFG4
C14	Fraction of grain in milk cow feed	not used	2.000E-01	---	AVFG5
STOR	Storage times of contaminated foodstuffs (days):				
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS
TITL	Maximum number of integration points for dose	17	---	---	LYMAX
TITL	Maximum number of integration points for risk	257	---	---	KYMAX

Summary of Pathway Selections

Pathway	User Selection
1 -- external gamma	active
2 -- inhalation (w/o radon)	active
3 -- plant ingestion	suppressed
4 -- meat ingestion	suppressed
5 -- milk ingestion	suppressed
6 -- aquatic foods	suppressed
7 -- drinking water	suppressed
8 -- soil ingestion	active
9 -- radon	suppressed
Find peak pathway doses	suppressed

Summary : Road Construction Worker - PG in Road Surface (Center)
File : C:\USERS\NEMICKASH\DESKTOP\FERTILIZER INSTITUTE\RESRAD\RCW_RS_CENTER_070319.RAD

Contaminated Zone Dimensions		Initial Soil Concentrations, pCi/g	
Area:	1500.00 square meters	Bi-210	6.100E-01
Thickness:	0.12 meters	Pb-210	6.100E-01
Cover Depth:	0.00 meters	Po-210	6.100E-01
		Ra-226	6.100E-01
		Rn-222	6.100E-01
		Th-230	1.100E-01
		Th-234	7.000E-02
		U-234	7.000E-02
		U-238	7.000E-02

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 2.500E+01 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0.000E+00	1.000E+00
TDOSE(t):	1.051E+00	1.016E+00
M(t):	4.206E-02	4.063E-02

Maximum TDOSE(t): 1.051E+00 mrem/yr at t = 0.000E+00 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	1.537E-05	0.0000	7.153E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.003E-04	0.0005
Pb-210	7.678E-04	0.0007	9.527E-04	0.0009	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.933E-02	0.0374
Po-210	2.419E-06	0.0000	2.439E-04	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.770E-02	0.0168
Ra-226	9.492E-01	0.9028	1.249E-03	0.0012	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.918E-03	0.0094
Rn-222	2.510E-02	0.0239	4.480E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.530E-05	0.0000
Th-230	6.165E-05	0.0001	2.375E-03	0.0023	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.298E-03	0.0012
Th-234	1.993E-04	0.0002	1.113E-08	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.274E-06	0.0000
U-234	4.985E-06	0.0000	1.395E-04	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.891E-04	0.0002
U-238	1.862E-03	0.0018	1.188E-04	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.856E-04	0.0002
Total	9.772E-01	0.9294	5.087E-03	0.0048	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.914E-02	0.0658

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.228E-04	0.0005
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.105E-02	0.0390
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.795E-02	0.0171
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.604E-01	0.9134
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.511E-02	0.0239
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.735E-03	0.0036
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.006E-04	0.0002
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.336E-04	0.0003
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.167E-03	0.0021
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.051E+00	1.0000

*Sum of all water independent and dependent pathways.

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	9.623E-09	0.0000	9.702E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.042E-05	0.0001
Pb-210	7.438E-04	0.0007	1.059E-03	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.850E-02	0.0477
Po-210	3.234E-07	0.0000	3.261E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.367E-03	0.0023
Ra-226	9.445E-01	0.9298	1.243E-03	0.0012	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.083E-02	0.0107
Rn-222	2.921E-07	0.0000	4.157E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.903E-05	0.0000
Th-230	1.364E-04	0.0001	2.375E-03	0.0023	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.299E-03	0.0013
Th-234	5.462E-09	0.0000	3.672E-11	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	8.428E-11	0.0000
U-234	4.805E-06	0.0000	1.345E-04	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.823E-04	0.0002
U-238	1.987E-03	0.0020	1.145E-04	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.801E-04	0.0002
Total	9.474E-01	0.9327	4.960E-03	0.0049	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.344E-02	0.0625

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.140E-05	0.0001
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.030E-02	0.0495
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.400E-03	0.0024
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.566E-01	0.9417
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.974E-05	0.0000
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.810E-03	0.0038
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.583E-09	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.216E-04	0.0003
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.282E-03	0.0022
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.016E+00	1.0000

*Sum of all water independent and dependent pathways.

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
Bi-210	Bi-210	1.000E+00	2.717E-05	7.209E-33	
Bi-210	Po-210	1.000E+00	8.299E-04	1.171E-04	
Bi-210	∑DSR(j)		8.571E-04	1.171E-04	
Pb-210	Pb-210	1.000E+00	3.940E-02	3.749E-02	
Pb-210	Bi-210	1.000E+00	9.196E-04	8.957E-04	
Pb-210	Po-210	1.000E+00	2.699E-02	4.408E-02	
Pb-210	∑DSR(j)		6.730E-02	8.246E-02	
Po-210	Po-210	1.000E+00	2.942E-02	3.934E-03	
Ra-226	Ra-226	1.000E+00	2.340E-02	2.278E-02	
Ra-226	Rn-222+D	1.000E+00	1.550E+00	1.543E+00	
Ra-226	Pb-210	1.000E+00	4.990E-04	1.472E-03	
Ra-226	Bi-210	1.000E+00	1.154E-05	3.478E-05	
Ra-226	Po-210	1.000E+00	2.535E-04	1.231E-03	
Ra-226	∑DSR(j)		1.574E+00	1.568E+00	
Rn-222+D	Rn-222+D	1.000E+00	4.114E-02	1.656E-36	
Rn-222+D	Pb-210	1.000E+00	1.513E-05	1.472E-05	
Rn-222+D	Bi-210	1.000E+00	3.596E-07	3.518E-07	
Rn-222+D	Po-210	1.000E+00	1.039E-05	1.728E-05	
Rn-222+D	∑DSR(j)		4.117E-02	3.235E-05	
Th-230	Th-230	1.000E+00	3.361E-02	3.361E-02	
Th-230	Ra-226	1.000E+00	5.092E-06	1.510E-05	
Th-230	Rn-222+D	1.000E+00	3.362E-04	1.013E-03	
Th-230	Pb-210	1.000E+00	7.161E-08	5.011E-07	
Th-230	Bi-210	1.000E+00	1.631E-09	1.173E-08	
Th-230	Po-210	1.000E+00	2.904E-08	3.362E-07	
Th-230	∑DSR(j)		3.395E-02	3.464E-02	
Th-234+D	Th-234+D	1.000E+00	2.866E-03	7.852E-08	
Th-234+D	U-234	1.000E+00	1.165E-09	1.244E-09	
Th-234+D	Th-230	1.000E+00	3.341E-14	1.116E-13	
Th-234+D	Ra-226	1.000E+00	3.130E-18	2.496E-17	
Th-234+D	Rn-222+D	1.000E+00	2.034E-16	1.661E-15	
Th-234+D	Pb-210	1.000E+00	3.029E-20	5.428E-19	
Th-234+D	Bi-210	1.000E+00	6.762E-22	1.257E-20	
Th-234+D	Po-210	1.000E+00	9.644E-21	3.002E-19	
Th-234+D	∑DSR(j)		2.866E-03	7.976E-08	

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
U-234	U-234	1.000E+00	4.766E-03	4.593E-03	
U-234	Th-230	1.000E+00	1.494E-07	4.411E-07	
U-234	Ra-226	1.000E+00	1.517E-11	1.043E-10	
U-234	Rn-222+D	1.000E+00	9.892E-10	6.948E-09	
U-234	Pb-210	1.000E+00	1.586E-13	2.385E-12	
U-234	Bi-210	1.000E+00	3.558E-15	5.531E-14	
U-234	Po-210	1.000E+00	5.350E-14	1.357E-12	
U-234	∑DSR(j)		4.766E-03	4.594E-03	
U-238	U-238	5.400E-05	2.265E-07	2.183E-07	
U-238	U-238	9.999E-01	4.194E-03	4.042E-03	
U-238	Th-234+D	9.999E-01	2.676E-02	2.856E-02	
U-238	U-234	9.999E-01	5.568E-09	1.831E-08	
U-238	Th-230	9.999E-01	1.073E-13	8.533E-13	
U-238	Ra-226	9.999E-01	7.605E-18	1.327E-16	
U-238	Rn-222+D	9.999E-01	4.880E-16	8.767E-15	
U-238	Pb-210	9.999E-01	5.856E-20	2.229E-18	
U-238	Bi-210	9.999E-01	1.287E-21	5.117E-20	
U-238	Po-210	9.999E-01	1.594E-20	1.076E-18	
U-238	∑DSR(j)		3.095E-02	3.260E-02	

The DSR includes contributions from associated (half-life ≤ 1 day) daughters.

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00
Bi-210	2.917E+04	2.136E+05
Pb-210	3.715E+02	3.032E+02
Po-210	8.497E+02	6.355E+03
Ra-226	1.588E+01	1.594E+01
Rn-222	6.073E+02	7.727E+05
Th-230	7.363E+02	7.217E+02
Th-234	8.723E+03	3.134E+08
U-234	5.245E+03	5.442E+03
U-238	8.077E+02	7.669E+02

Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Nuclide (i)	Initial (pCi/g)	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
Bi-210	6.100E-01	0.000E+00	8.571E-04	2.917E+04	8.571E-04	2.917E+04
Pb-210	6.100E-01	1.000E+00	8.246E-02	3.032E+02	6.730E-02	3.715E+02
Po-210	6.100E-01	0.000E+00	2.942E-02	8.497E+02	2.942E-02	8.497E+02
Ra-226	6.100E-01	0.0701 ± 0.0001	1.605E+00	1.557E+01	1.574E+00	1.588E+01
Rn-222	6.100E-01	0.000E+00	4.117E-02	6.073E+02	4.117E-02	6.073E+02
Th-230	1.100E-01	1.000E+00	3.464E-02	7.217E+02	3.395E-02	7.363E+02
Th-234	7.000E-02	0.000E+00	2.866E-03	8.723E+03	2.866E-03	8.723E+03
U-234	7.000E-02	0.000E+00	4.766E-03	5.245E+03	4.766E-03	5.245E+03
U-238	7.000E-02	0.3128 ± 0.0006	3.333E-02	7.501E+02	3.095E-02	8.077E+02

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.658E-05	0.000E+00
Bi-210	Pb-210	1.000E+00	5.610E-04	5.464E-04
Bi-210	Ra-226	1.000E+00	7.042E-06	2.122E-05
Bi-210	Rn-222	1.000E+00	2.194E-07	2.146E-07
Bi-210	Th-230	1.000E+00	1.794E-10	1.290E-09
Bi-210	Th-234	1.000E+00	4.734E-23	8.799E-22
Bi-210	U-234	1.000E+00	2.491E-16	3.872E-15
Bi-210	U-238	9.999E-01	9.009E-23	3.582E-21
Bi-210	∑DOSE(j)		5.848E-04	5.678E-04
Po-210	Bi-210	1.000E+00	5.062E-04	7.140E-05
Po-210	Pb-210	1.000E+00	1.646E-02	2.689E-02
Po-210	Po-210	1.000E+00	1.795E-02	2.400E-03
Po-210	Ra-226	1.000E+00	1.546E-04	7.510E-04
Po-210	Rn-222	1.000E+00	6.336E-06	1.054E-05
Po-210	Th-230	1.000E+00	3.194E-09	3.698E-08
Po-210	Th-234	1.000E+00	6.751E-22	2.101E-20
Po-210	U-234	1.000E+00	3.745E-15	9.497E-14
Po-210	U-238	9.999E-01	1.116E-21	7.535E-20
Po-210	∑DOSE(j)		3.508E-02	3.012E-02
Pb-210	Pb-210	1.000E+00	2.403E-02	2.287E-02
Pb-210	Ra-226	1.000E+00	3.044E-04	8.977E-04
Pb-210	Rn-222	1.000E+00	9.230E-06	8.981E-06
Pb-210	Th-230	1.000E+00	7.877E-09	5.512E-08
Pb-210	Th-234	1.000E+00	2.120E-21	3.800E-20
Pb-210	U-234	1.000E+00	1.110E-14	1.670E-13
Pb-210	U-238	9.999E-01	4.099E-21	1.561E-19
Pb-210	∑DOSE(j)		2.434E-02	2.378E-02
Ra-226	Ra-226	1.000E+00	1.428E-02	1.390E-02
Ra-226	Th-230	1.000E+00	5.601E-07	1.661E-06
Ra-226	Th-234	1.000E+00	2.191E-19	1.747E-18
Ra-226	U-234	1.000E+00	1.062E-12	7.301E-12
Ra-226	U-238	9.999E-01	5.323E-19	9.290E-18
Ra-226	∑DOSE(j)		1.428E-02	1.390E-02
Rn-222	Ra-226	1.000E+00	9.456E-01	9.410E-01
Rn-222	Rn-222	1.000E+00	2.510E-02	0.000E+00
Rn-222	Th-230	1.000E+00	3.698E-05	1.115E-04
Rn-222	Th-234	1.000E+00	1.424E-17	1.163E-16
Rn-222	U-234	1.000E+00	6.925E-11	4.863E-10
Rn-222	U-238	9.999E-01	3.416E-17	6.137E-16
Rn-222	∑DOSE(j)		9.708E-01	9.411E-01
Th-230	Th-230	1.000E+00	3.697E-03	3.697E-03
Th-230	Th-234	1.000E+00	2.339E-15	7.815E-15
Th-230	U-234	1.000E+00	1.046E-08	3.087E-08
Th-230	U-238	9.999E-01	7.512E-15	5.973E-14
Th-230	∑DOSE(j)		3.697E-03	3.697E-03

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	2.006E-04	5.496E-09
Th-234	U-238	9.999E-01	1.873E-03	1.999E-03
Th-234	∑DOSE(j)		2.074E-03	1.999E-03
U-234	Th-234	1.000E+00	8.158E-11	8.707E-11
U-234	U-234	1.000E+00	3.336E-04	3.215E-04
U-234	U-238	9.999E-01	3.898E-10	1.282E-09
U-234	∑DOSE(j)		3.336E-04	3.215E-04
U-238	U-238	5.400E-05	1.586E-08	1.528E-08
U-238	U-238	9.999E-01	2.936E-04	2.830E-04
U-238	∑DOSE(j)		2.936E-04	2.830E-04

THF(i) is the thread fraction of the parent nuclide.

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	6.100E-01	1.618E-28
Bi-210	Pb-210	1.000E+00	0.000E+00	4.622E-01
Bi-210	Ra-226	1.000E+00	0.000E+00	1.181E-02
Bi-210	Rn-222	1.000E+00	0.000E+00	1.815E-04
Bi-210	Th-230	1.000E+00	0.000E+00	4.539E-07
Bi-210	Th-234	1.000E+00	0.000E+00	1.723E-19
Bi-210	U-234	1.000E+00	0.000E+00	8.404E-13
Bi-210	U-238	9.999E-01	0.000E+00	4.076E-19
Bi-210	∑S(j):		6.100E-01	4.741E-01
Po-210	Bi-210	1.000E+00	0.000E+00	2.427E-03
Po-210	Pb-210	1.000E+00	0.000E+00	3.684E-01
Po-210	Po-210	1.000E+00	6.100E-01	8.156E-02
Po-210	Ra-226	1.000E+00	0.000E+00	6.076E-03
Po-210	Rn-222	1.000E+00	0.000E+00	1.440E-04
Po-210	Th-230	1.000E+00	0.000E+00	1.768E-07
Po-210	Th-234	1.000E+00	0.000E+00	5.159E-20
Po-210	U-234	1.000E+00	0.000E+00	2.657E-13
Po-210	U-238	9.999E-01	0.000E+00	1.032E-19
Po-210	∑S(j):		6.100E-01	4.586E-01
Pb-210	Pb-210	1.000E+00	6.100E-01	5.805E-01
Pb-210	Ra-226	1.000E+00	0.000E+00	1.507E-02
Pb-210	Rn-222	1.000E+00	0.000E+00	2.280E-04
Pb-210	Th-230	1.000E+00	0.000E+00	5.888E-07
Pb-210	Th-234	1.000E+00	0.000E+00	2.279E-19
Pb-210	U-234	1.000E+00	0.000E+00	1.107E-12
Pb-210	U-238	9.999E-01	0.000E+00	5.479E-19
Pb-210	∑S(j):		6.100E-01	5.958E-01
Ra-226	Ra-226	1.000E+00	6.100E-01	5.938E-01
Ra-226	Th-230	1.000E+00	0.000E+00	4.702E-05
Ra-226	Th-234	1.000E+00	0.000E+00	2.990E-17
Ra-226	U-234	1.000E+00	0.000E+00	1.336E-10
Ra-226	U-238	9.999E-01	0.000E+00	9.621E-17
Ra-226	∑S(j):		6.100E-01	5.939E-01
Rn-222	Ra-226	1.000E+00	0.000E+00	4.967E-01
Rn-222	Rn-222	1.000E+00	6.100E-01	2.455E-35
Rn-222	Th-230	1.000E+00	0.000E+00	3.882E-05
Rn-222	Th-234	1.000E+00	0.000E+00	2.432E-17
Rn-222	U-234	1.000E+00	0.000E+00	1.090E-10
Rn-222	U-238	9.999E-01	0.000E+00	7.725E-17
Rn-222	∑S(j):		6.100E-01	4.967E-01
Th-230	Th-230	1.000E+00	1.100E-01	1.100E-01
Th-230	Th-234	1.000E+00	0.000E+00	1.513E-13
Th-230	U-234	1.000E+00	0.000E+00	6.186E-07
Th-230	U-238	9.999E-01	0.000E+00	7.227E-13
Th-230	∑S(j):		1.100E-01	1.100E-01

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	7.000E-02	1.918E-06
Th-234	U-238	9.999E-01	0.000E+00	6.769E-02
Th-234	∑S(j):		7.000E-02	6.770E-02
U-234	Th-234	1.000E+00	0.000E+00	1.827E-08
U-234	U-234	1.000E+00	7.000E-02	6.746E-02
U-234	U-238	9.999E-01	0.000E+00	1.736E-07
U-234	∑S(j):		7.000E-02	6.746E-02
U-238	U-238	5.400E-05	3.780E-06	3.643E-06
U-238	U-238	9.999E-01	7.000E-02	6.746E-02
U-238	∑S(j):		7.000E-02	6.746E-02

THF(i) is the thread fraction of the parent nuclide.

RESCALC.EXE execution time = 25.33 seconds

RESRAD Modelling Results

Road Construction Worker – Road Surface_Edge

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Dose Conversion Factor (and Related) Parameter Summary
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
A-1	DCF's for external ground radiation, (mrem/yr)/(pCi/g)			
A-1	At-218 (Source: ICRP 60)	4.878E-03	4.878E-03	DCF1(1)
A-1	Bi-210 (Source: ICRP 60)	5.476E-03	5.476E-03	DCF1(2)
A-1	Bi-214 (Source: ICRP 60)	9.325E+00	9.325E+00	DCF1(3)
A-1	Pa-234 (Source: ICRP 60)	1.088E+01	1.088E+01	DCF1(4)
A-1	Pa-234m (Source: ICRP 60)	9.867E-02	9.867E-02	DCF1(5)
A-1	Pb-210 (Source: ICRP 60)	1.981E-03	1.981E-03	DCF1(6)
A-1	Pb-214 (Source: ICRP 60)	1.243E+00	1.243E+00	DCF1(7)
A-1	Po-210 (Source: ICRP 60)	4.934E-05	4.934E-05	DCF1(8)
A-1	Po-214 (Source: ICRP 60)	4.840E-04	4.840E-04	DCF1(9)
A-1	Po-218 (Source: ICRP 60)	5.326E-05	5.326E-05	DCF1(10)
A-1	Ra-226 (Source: ICRP 60)	2.915E-02	2.915E-02	DCF1(11)
A-1	Rn-222 (Source: ICRP 60)	2.186E-03	2.186E-03	DCF1(12)
A-1	Th-230 (Source: ICRP 60)	1.071E-03	1.071E-03	DCF1(13)
A-1	Th-234 (Source: ICRP 60)	2.130E-02	2.130E-02	DCF1(14)
A-1	Tl-210 (Source: ICRP 60)	1.661E+01	1.661E+01	DCF1(15)
A-1	U-234 (Source: ICRP 60)	3.439E-04	3.439E-04	DCF1(16)
A-1	U-238 (Source: ICRP 60)	7.961E-05	7.961E-05	DCF1(17)
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Bi-210	3.441E-04	3.441E-04	DCF2(1)
B-1	Pb-210	2.072E-02	2.072E-02	DCF2(2)
B-1	Po-210	1.591E-02	1.591E-02	DCF2(3)
B-1	Ra-226	3.515E-02	3.515E-02	DCF2(4)
B-1	Rn-222+D	1.073E-04	0.000E+00	DCF2(5)
B-1	Th-230	3.700E-01	3.700E-01	DCF2(6)
B-1	Th-234+D	2.849E-05	2.849E-05	DCF2(7)
B-1	U-234	3.478E-02	3.478E-02	DCF2(8)
B-1	U-238	2.960E-02	2.960E-02	DCF2(9)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Bi-210	4.810E-06	4.810E-06	DCF3(1)
D-1	Pb-210	2.553E-03	2.553E-03	DCF3(2)
D-1	Po-210	4.440E-03	4.440E-03	DCF3(3)
D-1	Ra-226	1.036E-03	1.036E-03	DCF3(4)
D-1	Rn-222+D	9.249E-07	0.000E+00	DCF3(5)
D-1	Th-230	7.770E-04	7.770E-04	DCF3(6)
D-1	Th-234+D	1.259E-05	1.258E-05	DCF3(7)
D-1	U-234	1.813E-04	1.813E-04	DCF3(8)
D-1	U-238	1.665E-04	1.665E-04	DCF3(9)
D-34	Food transfer factors:			
D-34	Bi-210 , plant/soil concentration ratio, dimensionless	1.000E-01	1.000E-01	RTF(1,1)
D-34	Bi-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(1,2)
D-34	Bi-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-04	5.000E-04	RTF(1,3)
D-34				
D-34	Pb-210 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(2,1)
D-34	Pb-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(2,2)
D-34	Pb-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(2,3)
D-34				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(3,1)
D-34	Po-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(3,2)
D-34	Po-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.400E-04	3.400E-04	RTF(3,3)
D-34				
D-34	Ra-226 , plant/soil concentration ratio, dimensionless	4.000E-02	4.000E-02	RTF(4,1)
D-34	Ra-226 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,2)
D-34	Ra-226 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,3)
D-34				
D-34	Rn-222+D , plant/soil concentration ratio, dimensionless	0.000E+00	0.000E+00	RTF(5,1)
D-34	Rn-222+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,2)
D-34	Rn-222+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,3)
D-34				
D-34	Th-230 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(6,1)
D-34	Th-230 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(6,2)
D-34	Th-230 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(6,3)
D-34				
D-34	Th-234+D , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(7,1)
D-34	Th-234+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(7,2)
D-34	Th-234+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	U-234 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(8,1)
D-34	U-234 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(8,2)
D-34	U-234 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(8,3)
D-34				
D-34	U-238 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(9,1)
D-34	U-238 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(9,2)
D-34	U-238 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(9,3)
D-5	Bioaccumulation factors, fresh water, L/kg:			
D-5	Bi-210 , fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Bi-210 , crustacea and mollusks	1.000E+01	1.000E+01	BIOFAC(1,2)
D-5				
D-5	Pb-210 , fish	3.000E+02	3.000E+02	BIOFAC(2,1)
D-5	Pb-210 , crustacea and mollusks	1.000E+02	1.000E+02	BIOFAC(2,2)
D-5				
D-5	Po-210 , fish	1.000E+02	1.000E+02	BIOFAC(3,1)
D-5	Po-210 , crustacea and mollusks	2.000E+04	2.000E+04	BIOFAC(3,2)
D-5				
D-5	Ra-226 , fish	5.000E+01	5.000E+01	BIOFAC(4,1)
D-5	Ra-226 , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(4,2)
D-5				
D-5	Rn-222+D , fish	0.000E+00	0.000E+00	BIOFAC(5,1)
D-5	Rn-222+D , crustacea and mollusks	0.000E+00	0.000E+00	BIOFAC(5,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(6,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(6,2)
D-5				
D-5	Th-234+D , fish	1.000E+02	1.000E+02	BIOFAC(7,1)
D-5	Th-234+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(7,2)
D-5				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-5	U-234 , fish	1.000E+01	1.000E+01	BIOFAC(8,1)
D-5	U-234 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(8,2)
D-5				
D-5	U-238 , fish	1.000E+01	1.000E+01	BIOFAC(9,1)
D-5	U-238 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(9,2)

#For DCF1(xxx) only, factors are for infinite depth & area. See ETFG table in Ground Pathway of Detailed Report.
*Base Case means Default.Lib w/o Associate Nuclide contributions.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.500E+03	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	1.200E-01	2.000E+00	---	THICK0
R011	Fraction of contamination that is submerged	0.000E+00	0.000E+00	---	SUBMFRACT
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	not used	3.000E+00	---	T(3)
R011	Times for calculations (yr)	not used	1.000E+01	---	T(4)
R011	Times for calculations (yr)	not used	3.000E+01	---	T(5)
R011	Times for calculations (yr)	not used	1.000E+02	---	T(6)
R011	Times for calculations (yr)	not used	3.000E+02	---	T(7)
R011	Times for calculations (yr)	not used	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Bi-210	6.100E-01	0.000E+00	---	S1(1)
R012	Initial principal radionuclide (pCi/g): Pb-210	6.100E-01	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Po-210	6.100E-01	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Ra-226	6.100E-01	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Rn-222	6.100E-01	0.000E+00	---	S1(5)
R012	Initial principal radionuclide (pCi/g): Th-230	1.100E-01	0.000E+00	---	S1(6)
R012	Initial principal radionuclide (pCi/g): Th-234	7.000E-02	0.000E+00	---	S1(7)
R012	Initial principal radionuclide (pCi/g): U-234	7.000E-02	0.000E+00	---	S1(8)
R012	Initial principal radionuclide (pCi/g): U-238	7.000E-02	0.000E+00	---	S1(9)
R012	Concentration in groundwater (pCi/L): Bi-210	not used	0.000E+00	---	W1(1)
R012	Concentration in groundwater (pCi/L): Pb-210	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Po-210	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Rn-222	not used	0.000E+00	---	W1(5)
R012	Concentration in groundwater (pCi/L): Th-230	not used	0.000E+00	---	W1(6)
R012	Concentration in groundwater (pCi/L): Th-234	not used	0.000E+00	---	W1(7)
R012	Concentration in groundwater (pCi/L): U-234	not used	0.000E+00	---	W1(8)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(9)
R013	Cover depth (m)	0.000E+00	0.000E+00	---	COVER0
R013	Density of cover material (g/cm**3)	not used	1.500E+00	---	DENSCV
R013	Cover depth erosion rate (m/yr)	not used	1.000E-03	---	VCV
R013	Density of contaminated zone (g/cm**3)	2.250E+00	1.500E+00	---	DENSCZ
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCZ
R013	Contaminated zone total porosity	4.000E-01	4.000E-01	---	TPCZ
R013	Contaminated zone field capacity	2.000E-01	2.000E-01	---	FCCZ
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01	---	HCCZ
R013	Contaminated zone b parameter	5.300E+00	5.300E+00	---	BCZ
R013	Average annual wind speed (m/sec)	2.000E+00	2.000E+00	---	WIND
R013	Humidity in air (g/m**3)	not used	8.000E+00	---	HUMID
R013	Evapotranspiration coefficient	5.000E-01	5.000E-01	---	EVAPTR
R013	Precipitation (m/yr)	1.000E+00	1.000E+00	---	PRECIP
R013	Irrigation (m/yr)	2.000E-01	2.000E-01	---	RI
R013	Irrigation mode	overhead	overhead	---	IDITCH

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R013	Runoff coefficient	2.000E-01	2.000E-01	---	RUNOFF
R013	Watershed area for nearby stream or pond (m**2)	not used	1.000E+06	---	WAREA
R013	Accuracy for water/soil computations	not used	1.000E-03	---	EPS
R014	Density of saturated zone (g/cm**3)	not used	1.500E+00	---	DENSAQ
R014	Saturated zone total porosity	not used	4.000E-01	---	TPSZ
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Bi-210				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.298E+01	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)
R016	Distribution coefficients for Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.849E-02	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(3)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(3,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(3)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.826E-01	ALEACH(3)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(3)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Ra-226				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(4)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(4,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(4)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	2.640E-02	ALEACH(4)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(4)
R016	Distribution coefficients for Rn-222				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(5)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(5,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(5)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.298E+01	ALEACH(5)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(5)
R016	Distribution coefficients for Th-230				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(6)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(6,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(6)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.086E-05	ALEACH(6)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(6)
R016	Distribution coefficients for Th-234				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(7)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(7,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(7)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.086E-05	ALEACH(7)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(7)
R016	Distribution coefficients for U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(8)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(8,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(8)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.693E-02	ALEACH(8)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(8)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.693E-02	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R017	Inhalation rate (m**3/yr)	1.140E+04	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	2.000E-04	1.000E-04	---	MLINH
R017	Exposure duration	1.000E+00	3.000E+01	---	ED
R017	Shielding factor, inhalation	4.000E-01	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	7.000E-01	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	0.000E+00	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	2.300E-01	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	-1.000E+00	1.000E+00	-1 shows non-circular AREA.	FS

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	4.417E+00	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	8.833E+00	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	1.325E+01	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	1.767E+01	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	2.208E+01	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	2.650E+01	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	3.092E+01	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	3.533E+01	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	3.975E+01	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	4.417E+01	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	4.858E+01	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	5.300E+01	0.000E+00	---	RAD_SHAPE(12)
R017	Fractions of annular areas within AREA:				
R017	Ring 1	5.000E-01	1.000E+00	---	FRACA(1)
R017	Ring 2	5.000E-01	2.732E-01	---	FRACA(2)
R017	Ring 3	5.000E-01	0.000E+00	---	FRACA(3)
R017	Ring 4	4.400E-01	0.000E+00	---	FRACA(4)
R017	Ring 5	2.800E-01	0.000E+00	---	FRACA(5)
R017	Ring 6	2.200E-01	0.000E+00	---	FRACA(6)
R017	Ring 7	1.800E-01	0.000E+00	---	FRACA(7)
R017	Ring 8	1.500E-01	0.000E+00	---	FRACA(8)
R017	Ring 9	1.300E-01	0.000E+00	---	FRACA(9)
R017	Ring 10	1.200E-01	0.000E+00	---	FRACA(10)
R017	Ring 11	1.100E-01	0.000E+00	---	FRACA(11)
R017	Ring 12	4.600E-02	0.000E+00	---	FRACA(12)
R018	Fruits, vegetables and grain consumption (kg/yr)	not used	1.600E+02	---	DIET(1)
R018	Leafy vegetable consumption (kg/yr)	not used	1.400E+01	---	DIET(2)
R018	Milk consumption (L/yr)	not used	9.200E+01	---	DIET(3)
R018	Meat and poultry consumption (kg/yr)	not used	6.300E+01	---	DIET(4)
R018	Fish consumption (kg/yr)	not used	5.400E+00	---	DIET(5)
R018	Other seafood consumption (kg/yr)	not used	9.000E-01	---	DIET(6)
R018	Soil ingestion rate (g/yr)	8.250E+01	3.650E+01	---	SOIL
R018	Drinking water intake (L/yr)	not used	5.100E+02	---	DWI
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)
R19B	Translocation Factor for Fodder	not used	1.000E+00	---	TIV(3)
R19B	Dry Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RDRY(1)
R19B	Dry Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RDRY(2)
R19B	Dry Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RDRY(3)
R19B	Wet Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RWET(1)
R19B	Wet Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RWET(2)
R19B	Wet Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RWET(3)
R19B	Weathering Removal Constant for Vegetation	not used	2.000E+01	---	WLAM
C14	C-12 concentration in water (g/cm**3)	not used	2.000E-05	---	C12WTR
C14	C-12 concentration in contaminated soil (g/g)	not used	3.000E-02	---	C12CZ
C14	Fraction of vegetation carbon from soil	not used	2.000E-02	---	CSOIL
C14	Fraction of vegetation carbon from air	not used	9.800E-01	---	CAIR
C14	C-14 evasion layer thickness in soil (m)	not used	3.000E-01	---	DMC
C14	C-14 evasion flux rate from soil (1/sec)	not used	7.000E-07	---	EVSN
C14	C-12 evasion flux rate from soil (1/sec)	not used	1.000E-10	---	REVSN
C14	Fraction of grain in beef cattle feed	not used	8.000E-01	---	AVFG4
C14	Fraction of grain in milk cow feed	not used	2.000E-01	---	AVFG5
STOR	Storage times of contaminated foodstuffs (days):				
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS
TITL	Maximum number of integration points for dose	17	---	---	LYMAX
TITL	Maximum number of integration points for risk	257	---	---	KYMAX

Summary of Pathway Selections

Pathway	User Selection
1 -- external gamma	active
2 -- inhalation (w/o radon)	active
3 -- plant ingestion	suppressed
4 -- meat ingestion	suppressed
5 -- milk ingestion	suppressed
6 -- aquatic foods	suppressed
7 -- drinking water	suppressed
8 -- soil ingestion	active
9 -- radon	suppressed
Find peak pathway doses	suppressed

Summary : Road Construction Worker - PG in Road Surface (Edge)
File : C:\USERS\NEMICKASH\DESKTOP\FERTILIZER INSTITUTE\RESRAD\RCW_RS_EDGE_070319.RAD

Contaminated Zone Dimensions	
Area:	1500.00 square meters
Thickness:	0.12 meters
Cover Depth:	0.00 meters

Initial Soil Concentrations, pCi/g	
Bi-210	6.100E-01
Pb-210	6.100E-01
Po-210	6.100E-01
Ra-226	6.100E-01
Rn-222	6.100E-01
Th-230	1.100E-01
Th-234	7.000E-02
U-234	7.000E-02
U-238	7.000E-02

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 2.500E+01 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0.000E+00	1.000E+00
TDOSE(t):	5.941E-01	5.724E-01
M(t):	2.376E-02	2.290E-02

Maximum TDOSE(t): 5.941E-01 mrem/yr at t = 0.000E+00 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	8.101E-06	0.0000	7.153E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.003E-04	0.0008
Pb-210	4.024E-04	0.0007	9.527E-04	0.0016	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.933E-02	0.0662
Po-210	1.284E-06	0.0000	2.439E-04	0.0004	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.770E-02	0.0298
Ra-226	5.050E-01	0.8500	1.249E-03	0.0021	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.918E-03	0.0167
Rn-222	1.335E-02	0.0225	4.480E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.530E-05	0.0000
Th-230	3.252E-05	0.0001	2.375E-03	0.0040	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.298E-03	0.0022
Th-234	1.055E-04	0.0002	1.113E-08	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.274E-06	0.0000
U-234	2.589E-06	0.0000	1.395E-04	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.891E-04	0.0003
U-238	9.851E-04	0.0017	1.188E-04	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.856E-04	0.0003
Total	5.199E-01	0.8751	5.087E-03	0.0086	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.914E-02	0.1164

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.155E-04	0.0009
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.069E-02	0.0685
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.795E-02	0.0302
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.161E-01	0.8688
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.337E-02	0.0225
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.706E-03	0.0062
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.067E-04	0.0002
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.312E-04	0.0006
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.290E-03	0.0022
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.941E-01	1.0000

*Sum of all water independent and dependent pathways.

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	5.107E-09	0.0000	9.702E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.042E-05	0.0001
Pb-210	3.899E-04	0.0007	1.059E-03	0.0019	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.850E-02	0.0847
Po-210	1.716E-07	0.0000	3.261E-05	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.367E-03	0.0041
Ra-226	5.025E-01	0.8779	1.243E-03	0.0022	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.083E-02	0.0189
Rn-222	1.531E-07	0.0000	4.157E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.903E-05	0.0000
Th-230	7.230E-05	0.0001	2.375E-03	0.0041	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.299E-03	0.0023
Th-234	2.890E-09	0.0000	3.672E-11	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	8.428E-11	0.0000
U-234	2.496E-06	0.0000	1.345E-04	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.823E-04	0.0003
U-238	1.051E-03	0.0018	1.145E-04	0.0002	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.801E-04	0.0003
Total	5.040E-01	0.8805	4.960E-03	0.0087	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.344E-02	0.1108

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.140E-05	0.0001
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.995E-02	0.0873
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.399E-03	0.0042
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.146E-01	0.8989
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.960E-05	0.0000
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.746E-03	0.0065
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.011E-09	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.192E-04	0.0006
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.346E-03	0.0024
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.724E-01	1.0000

*Sum of all water independent and dependent pathways.

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
Bi-210	Bi-210	1.000E+00	1.531E-05	4.061E-33	
Bi-210	Po-210	1.000E+00	8.298E-04	1.170E-04	
Bi-210	∑DSR(j)		8.451E-04	1.170E-04	
Pb-210	Pb-210	1.000E+00	3.920E-02	3.730E-02	
Pb-210	Bi-210	1.000E+00	5.181E-04	5.046E-04	
Pb-210	Po-210	1.000E+00	2.698E-02	4.407E-02	
Pb-210	∑DSR(j)		6.670E-02	8.188E-02	
Po-210	Po-210	1.000E+00	2.942E-02	3.934E-03	
Ra-226	Ra-226	1.000E+00	2.062E-02	2.007E-02	
Ra-226	Rn-222+D	1.000E+00	8.248E-01	8.208E-01	
Ra-226	Pb-210	1.000E+00	4.966E-04	1.464E-03	
Ra-226	Bi-210	1.000E+00	6.503E-06	1.959E-05	
Ra-226	Po-210	1.000E+00	2.535E-04	1.231E-03	
Ra-226	∑DSR(j)		8.461E-01	8.435E-01	
Rn-222+D	Rn-222+D	1.000E+00	2.189E-02	8.809E-37	
Rn-222+D	Pb-210	1.000E+00	1.506E-05	1.465E-05	
Rn-222+D	Bi-210	1.000E+00	2.026E-07	1.982E-07	
Rn-222+D	Po-210	1.000E+00	1.039E-05	1.728E-05	
Rn-222+D	∑DSR(j)		2.192E-02	3.213E-05	
Th-230	Th-230	1.000E+00	3.350E-02	3.350E-02	
Th-230	Ra-226	1.000E+00	4.486E-06	1.330E-05	
Th-230	Rn-222+D	1.000E+00	1.789E-04	5.391E-04	
Th-230	Pb-210	1.000E+00	7.125E-08	4.986E-07	
Th-230	Bi-210	1.000E+00	9.187E-10	6.606E-09	
Th-230	Po-210	1.000E+00	2.904E-08	3.362E-07	
Th-230	∑DSR(j)		3.369E-02	3.406E-02	
Th-234+D	Th-234+D	1.000E+00	1.525E-03	4.178E-08	
Th-234+D	U-234	1.000E+00	1.157E-09	1.235E-09	
Th-234+D	Th-230	1.000E+00	3.331E-14	1.113E-13	
Th-234+D	Ra-226	1.000E+00	2.757E-18	2.199E-17	
Th-234+D	Rn-222+D	1.000E+00	1.082E-16	8.838E-16	
Th-234+D	Pb-210	1.000E+00	3.014E-20	5.401E-19	
Th-234+D	Bi-210	1.000E+00	3.809E-22	7.081E-21	
Th-234+D	Po-210	1.000E+00	9.643E-21	3.002E-19	
Th-234+D	∑DSR(j)		1.525E-03	4.301E-08	

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
U-234	U-234	1.000E+00	4.732E-03	4.560E-03	
U-234	Th-230	1.000E+00	1.490E-07	4.397E-07	
U-234	Ra-226	1.000E+00	1.337E-11	9.188E-11	
U-234	Rn-222+D	1.000E+00	5.263E-10	3.696E-09	
U-234	Pb-210	1.000E+00	1.578E-13	2.373E-12	
U-234	Bi-210	1.000E+00	2.004E-15	3.116E-14	
U-234	Po-210	1.000E+00	5.350E-14	1.357E-12	
U-234	∑DSR(j)		4.732E-03	4.561E-03	
U-238	U-238	5.400E-05	2.261E-07	2.179E-07	
U-238	U-238	9.999E-01	4.186E-03	4.034E-03	
U-238	Th-234+D	9.999E-01	1.424E-02	1.519E-02	
U-238	U-234	9.999E-01	5.528E-09	1.818E-08	
U-238	Th-230	9.999E-01	1.070E-13	8.506E-13	
U-238	Ra-226	9.999E-01	6.699E-18	1.169E-16	
U-238	Rn-222+D	9.999E-01	2.596E-16	4.664E-15	
U-238	Pb-210	9.999E-01	5.827E-20	2.218E-18	
U-238	Bi-210	9.999E-01	7.250E-22	2.883E-20	
U-238	Po-210	9.999E-01	1.594E-20	1.076E-18	
U-238	∑DSR(j)		1.842E-02	1.923E-02	

The DSR includes contributions from associated (half-life ≤ 1 day) daughters.

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00
Bi-210	2.958E+04	2.136E+05
Pb-210	3.748E+02	3.053E+02
Po-210	8.498E+02	6.356E+03
Ra-226	2.955E+01	2.964E+01
Rn-222	1.141E+03	7.782E+05
Th-230	7.421E+02	7.341E+02
Th-234	1.639E+04	5.812E+08
U-234	5.283E+03	5.482E+03
U-238	1.357E+03	1.300E+03

Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Nuclide (i)	Initial (pCi/g)	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
Bi-210	6.100E-01	0.000E+00	8.451E-04	2.958E+04	8.451E-04	2.958E+04
Pb-210	6.100E-01	1.000E+00	8.188E-02	3.053E+02	6.670E-02	3.748E+02
Po-210	6.100E-01	0.000E+00	2.942E-02	8.498E+02	2.942E-02	8.498E+02
Ra-226	6.100E-01	0.0706 ± 0.0001	8.627E-01	2.898E+01	8.461E-01	2.955E+01
Rn-222	6.100E-01	0.000E+00	2.192E-02	1.141E+03	2.192E-02	1.141E+03
Th-230	1.100E-01	1.000E+00	3.406E-02	7.341E+02	3.369E-02	7.421E+02
Th-234	7.000E-02	0.000E+00	1.525E-03	1.639E+04	1.525E-03	1.639E+04
U-234	7.000E-02	0.000E+00	4.732E-03	5.283E+03	4.732E-03	5.283E+03
U-238	7.000E-02	0.2864 ± 0.0006	1.967E-02	1.271E+03	1.842E-02	1.357E+03

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	9.338E-06	0.000E+00
Bi-210	Pb-210	1.000E+00	3.160E-04	3.078E-04
Bi-210	Ra-226	1.000E+00	3.967E-06	1.195E-05
Bi-210	Rn-222	1.000E+00	1.236E-07	1.209E-07
Bi-210	Th-230	1.000E+00	1.011E-10	7.266E-10
Bi-210	Th-234	1.000E+00	2.667E-23	4.957E-22
Bi-210	U-234	1.000E+00	1.403E-16	2.181E-15
Bi-210	U-238	9.999E-01	5.075E-23	2.018E-21
Bi-210	∑DOSE(j)		3.294E-04	3.199E-04
Po-210	Bi-210	1.000E+00	5.062E-04	7.140E-05
Po-210	Pb-210	1.000E+00	1.646E-02	2.688E-02
Po-210	Po-210	1.000E+00	1.795E-02	2.399E-03
Po-210	Ra-226	1.000E+00	1.546E-04	7.510E-04
Po-210	Rn-222	1.000E+00	6.335E-06	1.054E-05
Po-210	Th-230	1.000E+00	3.194E-09	3.698E-08
Po-210	Th-234	1.000E+00	6.750E-22	2.101E-20
Po-210	U-234	1.000E+00	3.745E-15	9.497E-14
Po-210	U-238	9.999E-01	1.116E-21	7.535E-20
Po-210	∑DOSE(j)		3.507E-02	3.012E-02
Pb-210	Pb-210	1.000E+00	2.391E-02	2.276E-02
Pb-210	Ra-226	1.000E+00	3.029E-04	8.932E-04
Pb-210	Rn-222	1.000E+00	9.184E-06	8.936E-06
Pb-210	Th-230	1.000E+00	7.838E-09	5.485E-08
Pb-210	Th-234	1.000E+00	2.110E-21	3.781E-20
Pb-210	U-234	1.000E+00	1.105E-14	1.661E-13
Pb-210	U-238	9.999E-01	4.079E-21	1.553E-19
Pb-210	∑DOSE(j)		2.422E-02	2.366E-02
Ra-226	Ra-226	1.000E+00	1.258E-02	1.224E-02
Ra-226	Th-230	1.000E+00	4.934E-07	1.463E-06
Ra-226	Th-234	1.000E+00	1.930E-19	1.539E-18
Ra-226	U-234	1.000E+00	9.356E-13	6.431E-12
Ra-226	U-238	9.999E-01	4.689E-19	8.184E-18
Ra-226	∑DOSE(j)		1.258E-02	1.224E-02
Rn-222	Ra-226	1.000E+00	5.031E-01	5.007E-01
Rn-222	Rn-222	1.000E+00	1.335E-02	0.000E+00
Rn-222	Th-230	1.000E+00	1.967E-05	5.930E-05
Rn-222	Th-234	1.000E+00	7.577E-18	6.187E-17
Rn-222	U-234	1.000E+00	3.684E-11	2.587E-10
Rn-222	U-238	9.999E-01	1.817E-17	3.265E-16
Rn-222	∑DOSE(j)		5.165E-01	5.007E-01
Th-230	Th-230	1.000E+00	3.686E-03	3.685E-03
Th-230	Th-234	1.000E+00	2.332E-15	7.791E-15
Th-230	U-234	1.000E+00	1.043E-08	3.078E-08
Th-230	U-238	9.999E-01	7.488E-15	5.954E-14
Th-230	∑DOSE(j)		3.686E-03	3.685E-03

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.067E-04	2.924E-09
Th-234	U-238	9.999E-01	9.965E-04	1.064E-03
Th-234	∑DOSE(j)		1.103E-03	1.064E-03
U-234	Th-234	1.000E+00	8.100E-11	8.645E-11
U-234	U-234	1.000E+00	3.312E-04	3.192E-04
U-234	U-238	9.999E-01	3.870E-10	1.273E-09
U-234	∑DOSE(j)		3.312E-04	3.192E-04
U-238	U-238	5.400E-05	1.582E-08	1.525E-08
U-238	U-238	9.999E-01	2.930E-04	2.824E-04
U-238	∑DOSE(j)		2.930E-04	2.824E-04

THF(i) is the thread fraction of the parent nuclide.

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	6.100E-01	1.618E-28
Bi-210	Pb-210	1.000E+00	0.000E+00	4.622E-01
Bi-210	Ra-226	1.000E+00	0.000E+00	1.181E-02
Bi-210	Rn-222	1.000E+00	0.000E+00	1.815E-04
Bi-210	Th-230	1.000E+00	0.000E+00	4.539E-07
Bi-210	Th-234	1.000E+00	0.000E+00	1.723E-19
Bi-210	U-234	1.000E+00	0.000E+00	8.404E-13
Bi-210	U-238	9.999E-01	0.000E+00	4.076E-19
Bi-210	∑S(j):		6.100E-01	4.741E-01
Po-210	Bi-210	1.000E+00	0.000E+00	2.427E-03
Po-210	Pb-210	1.000E+00	0.000E+00	3.684E-01
Po-210	Po-210	1.000E+00	6.100E-01	8.156E-02
Po-210	Ra-226	1.000E+00	0.000E+00	6.076E-03
Po-210	Rn-222	1.000E+00	0.000E+00	1.440E-04
Po-210	Th-230	1.000E+00	0.000E+00	1.768E-07
Po-210	Th-234	1.000E+00	0.000E+00	5.159E-20
Po-210	U-234	1.000E+00	0.000E+00	2.657E-13
Po-210	U-238	9.999E-01	0.000E+00	1.032E-19
Po-210	∑S(j):		6.100E-01	4.586E-01
Pb-210	Pb-210	1.000E+00	6.100E-01	5.805E-01
Pb-210	Ra-226	1.000E+00	0.000E+00	1.507E-02
Pb-210	Rn-222	1.000E+00	0.000E+00	2.280E-04
Pb-210	Th-230	1.000E+00	0.000E+00	5.888E-07
Pb-210	Th-234	1.000E+00	0.000E+00	2.279E-19
Pb-210	U-234	1.000E+00	0.000E+00	1.107E-12
Pb-210	U-238	9.999E-01	0.000E+00	5.479E-19
Pb-210	∑S(j):		6.100E-01	5.958E-01
Ra-226	Ra-226	1.000E+00	6.100E-01	5.938E-01
Ra-226	Th-230	1.000E+00	0.000E+00	4.702E-05
Ra-226	Th-234	1.000E+00	0.000E+00	2.990E-17
Ra-226	U-234	1.000E+00	0.000E+00	1.336E-10
Ra-226	U-238	9.999E-01	0.000E+00	9.621E-17
Ra-226	∑S(j):		6.100E-01	5.939E-01
Rn-222	Ra-226	1.000E+00	0.000E+00	4.967E-01
Rn-222	Rn-222	1.000E+00	6.100E-01	2.455E-35
Rn-222	Th-230	1.000E+00	0.000E+00	3.882E-05
Rn-222	Th-234	1.000E+00	0.000E+00	2.432E-17
Rn-222	U-234	1.000E+00	0.000E+00	1.090E-10
Rn-222	U-238	9.999E-01	0.000E+00	7.725E-17
Rn-222	∑S(j):		6.100E-01	4.967E-01
Th-230	Th-230	1.000E+00	1.100E-01	1.100E-01
Th-230	Th-234	1.000E+00	0.000E+00	1.513E-13
Th-230	U-234	1.000E+00	0.000E+00	6.186E-07
Th-230	U-238	9.999E-01	0.000E+00	7.227E-13
Th-230	∑S(j):		1.100E-01	1.100E-01

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	7.000E-02	1.918E-06
Th-234	U-238	9.999E-01	0.000E+00	6.769E-02
Th-234	∑S(j):		7.000E-02	6.770E-02
U-234	Th-234	1.000E+00	0.000E+00	1.827E-08
U-234	U-234	1.000E+00	7.000E-02	6.746E-02
U-234	U-238	9.999E-01	0.000E+00	1.736E-07
U-234	∑S(j):		7.000E-02	6.746E-02
U-238	U-238	5.400E-05	3.780E-06	3.643E-06
U-238	U-238	9.999E-01	7.000E-02	6.746E-02
U-238	∑S(j):		7.000E-02	6.746E-02

THF(i) is the thread fraction of the parent nuclide.

RESCALC.EXE execution time = 30.97 seconds

RESRAD Modelling Results

Nearby Resident

Summary : Nearby Resident - PG in Road Base
File : C:\USERS\NEMICKASH\DESKTOP\FERTILIZER INSTITUTE\RESRAD\NR_RBS_070319.RAD

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Dose Conversion Factor (and Related) Parameter Summary
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
A-1	DCF's for external ground radiation, (mrem/yr)/(pCi/g)			
A-1	At-218 (Source: ICRP 60)	4.878E-03	4.878E-03	DCF1(1)
A-1	Bi-210 (Source: ICRP 60)	5.476E-03	5.476E-03	DCF1(2)
A-1	Bi-214 (Source: ICRP 60)	9.325E+00	9.325E+00	DCF1(3)
A-1	Pa-234 (Source: ICRP 60)	1.088E+01	1.088E+01	DCF1(4)
A-1	Pa-234m (Source: ICRP 60)	9.867E-02	9.867E-02	DCF1(5)
A-1	Pb-210 (Source: ICRP 60)	1.981E-03	1.981E-03	DCF1(6)
A-1	Pb-214 (Source: ICRP 60)	1.243E+00	1.243E+00	DCF1(7)
A-1	Po-210 (Source: ICRP 60)	4.934E-05	4.934E-05	DCF1(8)
A-1	Po-214 (Source: ICRP 60)	4.840E-04	4.840E-04	DCF1(9)
A-1	Po-218 (Source: ICRP 60)	5.326E-05	5.326E-05	DCF1(10)
A-1	Ra-226 (Source: ICRP 60)	2.915E-02	2.915E-02	DCF1(11)
A-1	Rn-222 (Source: ICRP 60)	2.186E-03	2.186E-03	DCF1(12)
A-1	Th-230 (Source: ICRP 60)	1.071E-03	1.071E-03	DCF1(13)
A-1	Th-234 (Source: ICRP 60)	2.130E-02	2.130E-02	DCF1(14)
A-1	Tl-210 (Source: ICRP 60)	1.661E+01	1.661E+01	DCF1(15)
A-1	U-234 (Source: ICRP 60)	3.439E-04	3.439E-04	DCF1(16)
A-1	U-238 (Source: ICRP 60)	7.961E-05	7.961E-05	DCF1(17)
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Bi-210	3.441E-04	3.441E-04	DCF2(1)
B-1	Pb-210	2.072E-02	2.072E-02	DCF2(2)
B-1	Po-210	1.591E-02	1.591E-02	DCF2(3)
B-1	Ra-226	3.515E-02	3.515E-02	DCF2(4)
B-1	Rn-222+D	1.073E-04	0.000E+00	DCF2(5)
B-1	Th-230	3.700E-01	3.700E-01	DCF2(6)
B-1	Th-234+D	2.849E-05	2.849E-05	DCF2(7)
B-1	U-234	3.478E-02	3.478E-02	DCF2(8)
B-1	U-238	2.960E-02	2.960E-02	DCF2(9)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Bi-210	4.810E-06	4.810E-06	DCF3(1)
D-1	Pb-210	2.553E-03	2.553E-03	DCF3(2)
D-1	Po-210	4.440E-03	4.440E-03	DCF3(3)
D-1	Ra-226	1.036E-03	1.036E-03	DCF3(4)
D-1	Rn-222+D	9.249E-07	0.000E+00	DCF3(5)
D-1	Th-230	7.770E-04	7.770E-04	DCF3(6)
D-1	Th-234+D	1.259E-05	1.258E-05	DCF3(7)
D-1	U-234	1.813E-04	1.813E-04	DCF3(8)
D-1	U-238	1.665E-04	1.665E-04	DCF3(9)
D-34	Food transfer factors:			
D-34	Bi-210 , plant/soil concentration ratio, dimensionless	1.000E-01	1.000E-01	RTF(1,1)
D-34	Bi-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(1,2)
D-34	Bi-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-04	5.000E-04	RTF(1,3)
D-34				
D-34	Pb-210 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(2,1)
D-34	Pb-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(2,2)
D-34	Pb-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(2,3)
D-34				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(3,1)
D-34	Po-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(3,2)
D-34	Po-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.400E-04	3.400E-04	RTF(3,3)
D-34				
D-34	Ra-226 , plant/soil concentration ratio, dimensionless	4.000E-02	4.000E-02	RTF(4,1)
D-34	Ra-226 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,2)
D-34	Ra-226 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,3)
D-34				
D-34	Rn-222+D , plant/soil concentration ratio, dimensionless	0.000E+00	0.000E+00	RTF(5,1)
D-34	Rn-222+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,2)
D-34	Rn-222+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,3)
D-34				
D-34	Th-230 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(6,1)
D-34	Th-230 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(6,2)
D-34	Th-230 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(6,3)
D-34				
D-34	Th-234+D , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(7,1)
D-34	Th-234+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(7,2)
D-34	Th-234+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	U-234 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(8,1)
D-34	U-234 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(8,2)
D-34	U-234 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(8,3)
D-34				
D-34	U-238 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(9,1)
D-34	U-238 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(9,2)
D-34	U-238 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(9,3)
D-5	Bioaccumulation factors, fresh water, L/kg:			
D-5	Bi-210 , fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Bi-210 , crustacea and mollusks	1.000E+01	1.000E+01	BIOFAC(1,2)
D-5				
D-5	Pb-210 , fish	3.000E+02	3.000E+02	BIOFAC(2,1)
D-5	Pb-210 , crustacea and mollusks	1.000E+02	1.000E+02	BIOFAC(2,2)
D-5				
D-5	Po-210 , fish	1.000E+02	1.000E+02	BIOFAC(3,1)
D-5	Po-210 , crustacea and mollusks	2.000E+04	2.000E+04	BIOFAC(3,2)
D-5				
D-5	Ra-226 , fish	5.000E+01	5.000E+01	BIOFAC(4,1)
D-5	Ra-226 , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(4,2)
D-5				
D-5	Rn-222+D , fish	0.000E+00	0.000E+00	BIOFAC(5,1)
D-5	Rn-222+D , crustacea and mollusks	0.000E+00	0.000E+00	BIOFAC(5,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(6,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(6,2)
D-5				
D-5	Th-234+D , fish	1.000E+02	1.000E+02	BIOFAC(7,1)
D-5	Th-234+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(7,2)
D-5				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-5	U-234 , fish	1.000E+01	1.000E+01	BIOFAC(8,1)
D-5	U-234 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(8,2)
D-5				
D-5	U-238 , fish	1.000E+01	1.000E+01	BIOFAC(9,1)
D-5	U-238 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(9,2)

#For DCF1(xxx) only, factors are for infinite depth & area. See ETFG table in Ground Pathway of Detailed Report.
*Base Case means Default.Lib w/o Associate Nuclide contributions.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.500E+03	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	2.500E-01	2.000E+00	---	THICK0
R011	Fraction of contamination that is submerged	0.000E+00	0.000E+00	---	SUBMFRACT
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	not used	3.000E+00	---	T(3)
R011	Times for calculations (yr)	not used	1.000E+01	---	T(4)
R011	Times for calculations (yr)	not used	3.000E+01	---	T(5)
R011	Times for calculations (yr)	not used	1.000E+02	---	T(6)
R011	Times for calculations (yr)	not used	3.000E+02	---	T(7)
R011	Times for calculations (yr)	not used	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Bi-210	1.350E+01	0.000E+00	---	S1(1)
R012	Initial principal radionuclide (pCi/g): Pb-210	1.350E+01	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Po-210	1.350E+01	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Ra-226	1.350E+01	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Rn-222	1.350E+01	0.000E+00	---	S1(5)
R012	Initial principal radionuclide (pCi/g): Th-230	2.500E+00	0.000E+00	---	S1(6)
R012	Initial principal radionuclide (pCi/g): Th-234	1.500E+00	0.000E+00	---	S1(7)
R012	Initial principal radionuclide (pCi/g): U-234	1.600E+00	0.000E+00	---	S1(8)
R012	Initial principal radionuclide (pCi/g): U-238	1.500E+00	0.000E+00	---	S1(9)
R012	Concentration in groundwater (pCi/L): Bi-210	not used	0.000E+00	---	W1(1)
R012	Concentration in groundwater (pCi/L): Pb-210	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Po-210	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Rn-222	not used	0.000E+00	---	W1(5)
R012	Concentration in groundwater (pCi/L): Th-230	not used	0.000E+00	---	W1(6)
R012	Concentration in groundwater (pCi/L): Th-234	not used	0.000E+00	---	W1(7)
R012	Concentration in groundwater (pCi/L): U-234	not used	0.000E+00	---	W1(8)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(9)
R013	Cover depth (m)	0.000E+00	0.000E+00	---	COVER0
R013	Density of cover material (g/cm**3)	not used	1.500E+00	---	DENSCV
R013	Cover depth erosion rate (m/yr)	not used	1.000E-03	---	VCV
R013	Density of contaminated zone (g/cm**3)	2.250E+00	1.500E+00	---	DENSCZ
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCZ
R013	Contaminated zone total porosity	4.000E-01	4.000E-01	---	TPCZ
R013	Contaminated zone field capacity	2.000E-01	2.000E-01	---	FCCZ
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01	---	HCCZ
R013	Contaminated zone b parameter	5.300E+00	5.300E+00	---	BCZ
R013	Average annual wind speed (m/sec)	2.000E+00	2.000E+00	---	WIND
R013	Humidity in air (g/m**3)	not used	8.000E+00	---	HUMID
R013	Evapotranspiration coefficient	5.000E-01	5.000E-01	---	EVAPTR
R013	Precipitation (m/yr)	1.000E+00	1.000E+00	---	PRECIP
R013	Irrigation (m/yr)	2.000E-01	2.000E-01	---	RI
R013	Irrigation mode	overhead	overhead	---	IDITCH

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R013	Runoff coefficient	2.000E-01	2.000E-01	---	RUNOFF
R013	Watershed area for nearby stream or pond (m**2)	not used	1.000E+06	---	WAREA
R013	Accuracy for water/soil computations	not used	1.000E-03	---	EPS
R014	Density of saturated zone (g/cm**3)	not used	1.500E+00	---	DENSAQ
R014	Saturated zone total porosity	not used	4.000E-01	---	TPSZ
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Bi-210				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)
R016	Distribution coefficients for Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.876E-03	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(3)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(3,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(3)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.764E-02	ALEACH(3)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(3)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Ra-226				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(4)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(4,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(4)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.267E-02	ALEACH(4)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(4)
R016	Distribution coefficients for Rn-222				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(5)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(5,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(5)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(5)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(5)
R016	Distribution coefficients for Th-230				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(6)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(6,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(6)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(6)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(6)
R016	Distribution coefficients for Th-234				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(7)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(7,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(7)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(7)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(7)
R016	Distribution coefficients for U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(8)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(8,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(8)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(8)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(8)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R017	Inhalation rate (m**3/yr)	8.400E+03	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	1.000E-04	1.000E-04	---	MLINH
R017	Exposure duration	1.000E+00	3.000E+01	---	ED
R017	Shielding factor, inhalation	4.000E-01	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	not used	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	5.000E-01	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	2.500E-01	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	not used	1.000E+00	-1 shows non-circular AREA.	FS

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	5.167E+00	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	1.033E+01	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	1.550E+01	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	2.067E+01	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	2.583E+01	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	3.100E+01	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	3.617E+01	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	4.133E+01	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	4.650E+01	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	5.167E+01	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	5.683E+01	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	6.200E+01	0.000E+00	---	RAD_SHAPE(12)
R017	Fractions of annular areas within AREA:				
R017	Ring 1	0.000E+00	1.000E+00	---	FRACA(1)
R017	Ring 2	0.000E+00	2.732E-01	---	FRACA(2)
R017	Ring 3	0.000E+00	0.000E+00	---	FRACA(3)
R017	Ring 4	6.500E-03	0.000E+00	---	FRACA(4)
R017	Ring 5	1.600E-01	0.000E+00	---	FRACA(5)
R017	Ring 6	2.500E-01	0.000E+00	---	FRACA(6)
R017	Ring 7	2.800E-01	0.000E+00	---	FRACA(7)
R017	Ring 8	1.900E-01	0.000E+00	---	FRACA(8)
R017	Ring 9	1.400E-01	0.000E+00	---	FRACA(9)
R017	Ring 10	1.200E-01	0.000E+00	---	FRACA(10)
R017	Ring 11	9.200E-02	0.000E+00	---	FRACA(11)
R017	Ring 12	2.300E-02	0.000E+00	---	FRACA(12)
R018	Fruits, vegetables and grain consumption (kg/yr)	not used	1.600E+02	---	DIET(1)
R018	Leafy vegetable consumption (kg/yr)	not used	1.400E+01	---	DIET(2)
R018	Milk consumption (L/yr)	not used	9.200E+01	---	DIET(3)
R018	Meat and poultry consumption (kg/yr)	not used	6.300E+01	---	DIET(4)
R018	Fish consumption (kg/yr)	not used	5.400E+00	---	DIET(5)
R018	Other seafood consumption (kg/yr)	not used	9.000E-01	---	DIET(6)
R018	Soil ingestion rate (g/yr)	3.650E+01	3.650E+01	---	SOIL
R018	Drinking water intake (L/yr)	not used	5.100E+02	---	DWI
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)
R19B	Translocation Factor for Fodder	not used	1.000E+00	---	TIV(3)
R19B	Dry Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RDRY(1)
R19B	Dry Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RDRY(2)
R19B	Dry Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RDRY(3)
R19B	Wet Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RWET(1)
R19B	Wet Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RWET(2)
R19B	Wet Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RWET(3)
R19B	Weathering Removal Constant for Vegetation	not used	2.000E+01	---	WLAM
C14	C-12 concentration in water (g/cm**3)	not used	2.000E-05	---	C12WTR
C14	C-12 concentration in contaminated soil (g/g)	not used	3.000E-02	---	C12CZ
C14	Fraction of vegetation carbon from soil	not used	2.000E-02	---	CSOIL
C14	Fraction of vegetation carbon from air	not used	9.800E-01	---	CAIR
C14	C-14 evasion layer thickness in soil (m)	not used	3.000E-01	---	DMC
C14	C-14 evasion flux rate from soil (1/sec)	not used	7.000E-07	---	EVSN
C14	C-12 evasion flux rate from soil (1/sec)	not used	1.000E-10	---	REVSN
C14	Fraction of grain in beef cattle feed	not used	8.000E-01	---	AVFG4
C14	Fraction of grain in milk cow feed	not used	2.000E-01	---	AVFG5
STOR	Storage times of contaminated foodstuffs (days):				
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS
TITL	Maximum number of integration points for dose	17	---	---	LYMAX
TITL	Maximum number of integration points for risk	257	---	---	KYMAX

Summary of Pathway Selections

Pathway	User Selection
1 -- external gamma	suppressed
2 -- inhalation (w/o radon)	active
3 -- plant ingestion	suppressed
4 -- meat ingestion	suppressed
5 -- milk ingestion	suppressed
6 -- aquatic foods	suppressed
7 -- drinking water	suppressed
8 -- soil ingestion	active
9 -- radon	suppressed
Find peak pathway doses	suppressed

Summary : Nearby Resident - PG in Road Base
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Contaminated Zone Dimensions	
Area:	1500.00 square meters
Thickness:	0.25 meters
Cover Depth:	0.00 meters

Initial Soil Concentrations, pCi/g	
Bi-210	1.350E+01
Pb-210	1.350E+01
Po-210	1.350E+01
Ra-226	1.350E+01
Rn-222	1.350E+01
Th-230	2.500E+00
Th-234	1.500E+00
U-234	1.600E+00
U-238	1.500E+00

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 2.500E+01 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0.000E+00	1.000E+00
TDOSE(t):	2.996E+00	2.870E+00
M(t):	1.198E-01	1.148E-01

Maximum TDOSE(t): 2.996E+00 mrem/yr at t = 0.000E+00 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	1.646E-04	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.313E-02	0.0077
Pb-210	0.000E+00	0.0000	1.974E-02	0.0066	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.669E+00	0.5570
Po-210	0.000E+00	0.0000	5.025E-03	0.0017	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.300E-01	0.2437
Ra-226	0.000E+00	0.0000	2.511E-02	0.0084	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.011E-01	0.1339
Rn-222	0.000E+00	0.0000	9.942E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.079E-04	0.0002
Th-230	0.000E+00	0.0000	4.864E-02	0.0162	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.319E-02	0.0178
Th-234	0.000E+00	0.0000	2.148E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.925E-05	0.0000
U-234	0.000E+00	0.0000	2.901E-03	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.871E-03	0.0026
U-238	0.000E+00	0.0000	2.316E-03	0.0008	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.240E-03	0.0024
Total	0.000E+00	0.0000	1.039E-01	0.0347	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.892E+00	0.9653

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.329E-02	0.0078
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.688E+00	0.5636
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.351E-01	0.2454
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.262E-01	0.1423
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.178E-04	0.0002
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.018E-01	0.0340
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.946E-05	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.077E-02	0.0036
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.557E-03	0.0032
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.996E+00	1.0000

*Sum of all water independent and dependent pathways.

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	2.465E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.582E-03	0.0012
Pb-210	0.000E+00	0.0000	2.263E-02	0.0079	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.136E+00	0.7441
Po-210	0.000E+00	0.0000	7.388E-04	0.0003	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.073E-01	0.0374
Ra-226	0.000E+00	0.0000	2.540E-02	0.0089	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.517E-01	0.1574
Rn-222	0.000E+00	0.0000	9.708E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.156E-04	0.0003
Th-230	0.000E+00	0.0000	4.864E-02	0.0170	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.322E-02	0.0185
Th-234	0.000E+00	0.0000	7.281E-10	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.309E-09	0.0000
U-234	0.000E+00	0.0000	2.850E-03	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.733E-03	0.0027
U-238	0.000E+00	0.0000	2.276E-03	0.0008	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.162E-03	0.0025
Total	0.000E+00	0.0000	1.026E-01	0.0357	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.767E+00	0.9643

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.606E-03	0.0013
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.158E+00	0.7520
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.081E-01	0.0377
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.771E-01	0.1663
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.254E-04	0.0003
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.019E-01	0.0355
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.037E-09	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.058E-02	0.0037
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.438E-03	0.0033
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.870E+00	1.0000

*Sum of all water independent and dependent pathways.

Summary : Nearby Resident - PG in Road Base
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Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
Bi-210	Bi-210	1.000E+00	3.485E-06	7.908E-31	
Bi-210	Po-210	1.000E+00	1.722E-03	2.671E-04	
Bi-210	∑DSR(j)		1.725E-03	2.671E-04	
Pb-210	Pb-210	1.000E+00	6.958E-02	6.685E-02	
Pb-210	Bi-210	1.000E+00	1.277E-04	1.257E-04	
Pb-210	Po-210	1.000E+00	5.535E-02	9.289E-02	
Pb-210	∑DSR(j)		1.251E-01	1.599E-01	
Po-210	Po-210	1.000E+00	5.445E-02	8.005E-03	
Ra-226	Ra-226	1.000E+00	3.001E-02	2.962E-02	
Ra-226	Rn-222+D	1.000E+00	2.750E-05	2.775E-05	
Ra-226	Pb-210	1.000E+00	9.640E-04	2.877E-03	
Ra-226	Bi-210	1.000E+00	1.748E-06	5.342E-06	
Ra-226	Po-210	1.000E+00	5.641E-04	2.811E-03	
Ra-226	∑DSR(j)		3.157E-02	3.534E-02	
Rn-222+D	Rn-222+D	1.000E+00	6.730E-07	2.317E-38	
Rn-222+D	Pb-210	1.000E+00	2.921E-05	2.870E-05	
Rn-222+D	Bi-210	1.000E+00	5.449E-08	5.394E-08	
Rn-222+D	Po-210	1.000E+00	2.324E-05	3.979E-05	
Rn-222+D	∑DSR(j)		5.317E-05	6.854E-05	
Th-230	Th-230	1.000E+00	4.073E-02	4.073E-02	
Th-230	Ra-226	1.000E+00	6.515E-06	1.943E-05	
Th-230	Rn-222+D	1.000E+00	5.938E-09	1.804E-08	
Th-230	Pb-210	1.000E+00	1.379E-07	9.735E-07	
Th-230	Bi-210	1.000E+00	2.457E-10	1.788E-09	
Th-230	Po-210	1.000E+00	6.414E-08	7.589E-07	
Th-230	∑DSR(j)		4.073E-02	4.075E-02	
Th-234+D	Th-234+D	1.000E+00	3.297E-05	9.033E-10	
Th-234+D	U-234	1.000E+00	1.645E-09	1.788E-09	
Th-234+D	Th-230	1.000E+00	4.073E-14	1.372E-13	
Th-234+D	Ra-226	1.000E+00	4.017E-18	3.233E-17	
Th-234+D	Rn-222+D	1.000E+00	3.600E-21	2.972E-20	
Th-234+D	Pb-210	1.000E+00	5.838E-20	1.058E-18	
Th-234+D	Bi-210	1.000E+00	1.017E-22	1.921E-21	
Th-234+D	Po-210	1.000E+00	2.120E-20	6.763E-19	
Th-234+D	∑DSR(j)		3.297E-05	2.691E-09	

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
U-234	U-234	1.000E+00	6.732E-03	6.614E-03	
U-234	Th-230	1.000E+00	1.822E-07	5.424E-07	
U-234	Ra-226	1.000E+00	1.948E-11	1.352E-10	
U-234	Rn-222+D	1.000E+00	1.752E-14	1.244E-13	
U-234	Pb-210	1.000E+00	3.060E-13	4.653E-12	
U-234	Bi-210	1.000E+00	5.359E-16	8.460E-15	
U-234	Po-210	1.000E+00	1.179E-13	3.062E-12	
U-234	∑DSR(j)		6.732E-03	6.614E-03	
U-238	U-238	5.400E-05	3.273E-07	3.215E-07	
U-238	U-238	9.999E-01	6.060E-03	5.954E-03	
U-238	Th-234+D	9.999E-01	3.105E-04	3.375E-04	
U-238	U-234	9.999E-01	7.883E-09	2.635E-08	
U-238	Th-230	9.999E-01	1.312E-13	1.054E-12	
U-238	Ra-226	9.999E-01	9.780E-18	1.725E-16	
U-238	Rn-222+D	9.999E-01	8.641E-21	1.574E-19	
U-238	Pb-210	9.999E-01	1.129E-19	4.357E-18	
U-238	Bi-210	9.999E-01	1.934E-22	7.831E-21	
U-238	Po-210	9.999E-01	3.494E-20	2.423E-18	
U-238	∑DSR(j)		6.371E-03	6.291E-03	

The DSR includes contributions from associated (half-life ≤ 1 day) daughters.

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00
Bi-210	1.449E+04	9.359E+04
Pb-210	1.999E+02	1.564E+02
Po-210	4.591E+02	3.123E+03
Ra-226	7.919E+02	7.074E+02
Rn-222	4.702E+05	3.647E+05
Th-230	6.137E+02	6.135E+02
Th-234	7.582E+05	9.289E+09
U-234	3.713E+03	3.780E+03
U-238	3.924E+03	3.973E+03

Summary : Nearby Resident - PG in Road Base
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Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Nuclide (i)	Initial (pCi/g)	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
Bi-210	1.350E+01	0.000E+00	1.725E-03	1.449E+04	1.725E-03	1.449E+04
Pb-210	1.350E+01	1.000E+00	1.599E-01	1.564E+02	1.251E-01	1.999E+02
Po-210	1.350E+01	0.000E+00	5.445E-02	4.591E+02	5.445E-02	4.591E+02
Ra-226	1.350E+01	1.000E+00	3.534E-02	7.074E+02	3.157E-02	7.919E+02
Rn-222	1.350E+01	1.000E+00	6.854E-05	3.647E+05	5.317E-05	4.702E+05
Th-230	2.500E+00	1.000E+00	4.075E-02	6.135E+02	4.073E-02	6.137E+02
Th-234	1.500E+00	0.000E+00	3.297E-05	7.582E+05	3.297E-05	7.582E+05
U-234	1.600E+00	0.000E+00	6.732E-03	3.713E+03	6.732E-03	3.713E+03
U-238	1.500E+00	0.1075 ± 0.0002	6.381E-03	3.918E+03	6.371E-03	3.924E+03

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	4.705E-05	0.000E+00
Bi-210	Pb-210	1.000E+00	1.724E-03	1.696E-03
Bi-210	Ra-226	1.000E+00	2.359E-05	7.212E-05
Bi-210	Rn-222	1.000E+00	7.357E-07	7.282E-07
Bi-210	Th-230	1.000E+00	6.143E-10	4.469E-09
Bi-210	Th-234	1.000E+00	1.526E-22	2.881E-21
Bi-210	U-234	1.000E+00	8.575E-16	1.354E-14
Bi-210	U-238	9.999E-01	2.900E-22	1.175E-20
Bi-210	∑DOSE(j)		1.795E-03	1.769E-03
Po-210	Bi-210	1.000E+00	2.325E-02	3.606E-03
Po-210	Pb-210	1.000E+00	7.472E-01	1.254E+00
Po-210	Po-210	1.000E+00	7.351E-01	1.081E-01
Po-210	Ra-226	1.000E+00	7.615E-03	3.794E-02
Po-210	Rn-222	1.000E+00	3.137E-04	5.372E-04
Po-210	Th-230	1.000E+00	1.603E-07	1.897E-06
Po-210	Th-234	1.000E+00	3.180E-20	1.015E-18
Po-210	U-234	1.000E+00	1.886E-13	4.899E-12
Po-210	U-238	9.999E-01	5.241E-20	3.635E-18
Po-210	∑DOSE(j)		1.513E+00	1.404E+00
Pb-210	Pb-210	1.000E+00	9.393E-01	9.025E-01
Pb-210	Ra-226	1.000E+00	1.301E-02	3.884E-02
Pb-210	Rn-222	1.000E+00	3.943E-04	3.874E-04
Pb-210	Th-230	1.000E+00	3.448E-07	2.434E-06
Pb-210	Th-234	1.000E+00	8.757E-20	1.587E-18
Pb-210	U-234	1.000E+00	4.896E-13	7.446E-12
Pb-210	U-238	9.999E-01	1.694E-19	6.536E-18
Pb-210	∑DOSE(j)		9.527E-01	9.417E-01
Ra-226	Ra-226	1.000E+00	4.052E-01	3.999E-01
Ra-226	Th-230	1.000E+00	1.629E-05	4.858E-05
Ra-226	Th-234	1.000E+00	6.026E-18	4.849E-17
Ra-226	U-234	1.000E+00	3.117E-11	2.163E-10
Ra-226	U-238	9.999E-01	1.467E-17	2.588E-16
Ra-226	∑DOSE(j)		4.052E-01	3.999E-01
Rn-222	Ra-226	1.000E+00	3.713E-04	3.747E-04
Rn-222	Rn-222	1.000E+00	9.086E-06	0.000E+00
Rn-222	Th-230	1.000E+00	1.485E-08	4.509E-08
Rn-222	Th-234	1.000E+00	5.399E-21	4.458E-20
Rn-222	U-234	1.000E+00	2.803E-14	1.991E-13
Rn-222	U-238	9.999E-01	1.296E-20	2.360E-19
Rn-222	∑DOSE(j)		3.804E-04	3.747E-04
Th-230	Th-230	1.000E+00	1.018E-01	1.018E-01
Th-230	Th-234	1.000E+00	6.109E-14	2.058E-13
Th-230	U-234	1.000E+00	2.916E-07	8.679E-07
Th-230	U-238	9.999E-01	1.968E-13	1.581E-12
Th-230	∑DOSE(j)		1.018E-01	1.018E-01

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	4.946E-05	1.355E-09
Th-234	U-238	9.999E-01	4.658E-04	5.063E-04
Th-234	∑DOSE(j)		5.153E-04	5.063E-04
U-234	Th-234	1.000E+00	2.467E-09	2.682E-09
U-234	U-234	1.000E+00	1.077E-02	1.058E-02
U-234	U-238	9.999E-01	1.182E-08	3.953E-08
U-234	∑DOSE(j)		1.077E-02	1.058E-02
U-238	U-238	5.400E-05	4.909E-07	4.823E-07
U-238	U-238	9.999E-01	9.090E-03	8.931E-03
U-238	∑DOSE(j)		9.091E-03	8.931E-03

THF(i) is the thread fraction of the parent nuclide.

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.350E+01	3.063E-24
Bi-210	Pb-210	1.000E+00	0.000E+00	1.155E+01
Bi-210	Ra-226	1.000E+00	0.000E+00	3.223E-01
Bi-210	Rn-222	1.000E+00	0.000E+00	4.960E-03
Bi-210	Th-230	1.000E+00	0.000E+00	1.264E-05
Bi-210	Th-234	1.000E+00	0.000E+00	4.515E-18
Bi-210	U-234	1.000E+00	0.000E+00	2.353E-11
Bi-210	U-238	9.999E-01	0.000E+00	1.067E-17
Bi-210	∑S(j):		1.350E+01	1.188E+01
Po-210	Bi-210	1.000E+00	0.000E+00	6.623E-02
Po-210	Pb-210	1.000E+00	0.000E+00	9.479E+00
Po-210	Po-210	1.000E+00	1.350E+01	1.985E+00
Po-210	Ra-226	1.000E+00	0.000E+00	1.689E-01
Po-210	Rn-222	1.000E+00	0.000E+00	4.049E-03
Po-210	Th-230	1.000E+00	0.000E+00	4.992E-06
Po-210	Th-234	1.000E+00	0.000E+00	1.366E-18
Po-210	U-234	1.000E+00	0.000E+00	7.521E-12
Po-210	U-238	9.999E-01	0.000E+00	2.722E-18
Po-210	∑S(j):		1.350E+01	1.170E+01
Pb-210	Pb-210	1.000E+00	1.350E+01	1.297E+01
Pb-210	Ra-226	1.000E+00	0.000E+00	3.685E-01
Pb-210	Rn-222	1.000E+00	0.000E+00	5.568E-03
Pb-210	Th-230	1.000E+00	0.000E+00	1.471E-05
Pb-210	Th-234	1.000E+00	0.000E+00	5.371E-18
Pb-210	U-234	1.000E+00	0.000E+00	2.786E-11
Pb-210	U-238	9.999E-01	0.000E+00	1.292E-17
Pb-210	∑S(j):		1.350E+01	1.335E+01
Ra-226	Ra-226	1.000E+00	1.350E+01	1.332E+01
Ra-226	Th-230	1.000E+00	0.000E+00	1.076E-03
Ra-226	Th-234	1.000E+00	0.000E+00	6.472E-16
Ra-226	U-234	1.000E+00	0.000E+00	3.088E-09
Ra-226	U-238	9.999E-01	0.000E+00	2.087E-15
Ra-226	∑S(j):		1.350E+01	1.333E+01
Rn-222	Ra-226	1.000E+00	0.000E+00	1.218E+01
Rn-222	Rn-222	1.000E+00	1.350E+01	4.647E-31
Rn-222	Th-230	1.000E+00	0.000E+00	9.699E-04
Rn-222	Th-234	1.000E+00	0.000E+00	5.740E-16
Rn-222	U-234	1.000E+00	0.000E+00	2.746E-09
Rn-222	U-238	9.999E-01	0.000E+00	1.825E-15
Rn-222	∑S(j):		1.350E+01	1.218E+01
Th-230	Th-230	1.000E+00	2.500E+00	2.500E+00
Th-230	Th-234	1.000E+00	0.000E+00	3.270E-12
Th-230	U-234	1.000E+00	0.000E+00	1.428E-05
Th-230	U-238	9.999E-01	0.000E+00	1.567E-11
Th-230	∑S(j):		2.500E+00	2.500E+00

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.500E+00	4.110E-05
Th-234	U-238	9.999E-01	0.000E+00	1.476E+00
Th-234	∑S(j):		1.500E+00	1.476E+00
U-234	Th-234	1.000E+00	0.000E+00	3.983E-07
U-234	U-234	1.000E+00	1.600E+00	1.572E+00
U-234	U-238	9.999E-01	0.000E+00	3.786E-06
U-234	∑S(j):		1.600E+00	1.572E+00
U-238	U-238	5.400E-05	8.100E-05	7.958E-05
U-238	U-238	9.999E-01	1.500E+00	1.474E+00
U-238	∑S(j):		1.500E+00	1.474E+00

THF(i) is the thread fraction of the parent nuclide.

RESCALC.EXE execution time = 21.37 seconds

RESRAD Modelling Results

Utility Worker

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Dose Conversion Factor (and Related) Parameter Summary
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
A-1	DCF's for external ground radiation, (mrem/yr)/(pCi/g)			
A-1	At-218 (Source: ICRP 60)	4.878E-03	4.878E-03	DCF1(1)
A-1	Bi-210 (Source: ICRP 60)	5.476E-03	5.476E-03	DCF1(2)
A-1	Bi-214 (Source: ICRP 60)	9.325E+00	9.325E+00	DCF1(3)
A-1	Pa-234 (Source: ICRP 60)	1.088E+01	1.088E+01	DCF1(4)
A-1	Pa-234m (Source: ICRP 60)	9.867E-02	9.867E-02	DCF1(5)
A-1	Pb-210 (Source: ICRP 60)	1.981E-03	1.981E-03	DCF1(6)
A-1	Pb-214 (Source: ICRP 60)	1.243E+00	1.243E+00	DCF1(7)
A-1	Po-210 (Source: ICRP 60)	4.934E-05	4.934E-05	DCF1(8)
A-1	Po-214 (Source: ICRP 60)	4.840E-04	4.840E-04	DCF1(9)
A-1	Po-218 (Source: ICRP 60)	5.326E-05	5.326E-05	DCF1(10)
A-1	Ra-226 (Source: ICRP 60)	2.915E-02	2.915E-02	DCF1(11)
A-1	Rn-222 (Source: ICRP 60)	2.186E-03	2.186E-03	DCF1(12)
A-1	Th-230 (Source: ICRP 60)	1.071E-03	1.071E-03	DCF1(13)
A-1	Th-234 (Source: ICRP 60)	2.130E-02	2.130E-02	DCF1(14)
A-1	Tl-210 (Source: ICRP 60)	1.661E+01	1.661E+01	DCF1(15)
A-1	U-234 (Source: ICRP 60)	3.439E-04	3.439E-04	DCF1(16)
A-1	U-238 (Source: ICRP 60)	7.961E-05	7.961E-05	DCF1(17)
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Bi-210	3.441E-04	3.441E-04	DCF2(1)
B-1	Pb-210	2.072E-02	2.072E-02	DCF2(2)
B-1	Po-210	1.591E-02	1.591E-02	DCF2(3)
B-1	Ra-226	3.515E-02	3.515E-02	DCF2(4)
B-1	Rn-222+D	1.073E-04	0.000E+00	DCF2(5)
B-1	Th-230	3.700E-01	3.700E-01	DCF2(6)
B-1	Th-234+D	2.849E-05	2.849E-05	DCF2(7)
B-1	U-234	3.478E-02	3.478E-02	DCF2(8)
B-1	U-238	2.960E-02	2.960E-02	DCF2(9)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Bi-210	4.810E-06	4.810E-06	DCF3(1)
D-1	Pb-210	2.553E-03	2.553E-03	DCF3(2)
D-1	Po-210	4.440E-03	4.440E-03	DCF3(3)
D-1	Ra-226	1.036E-03	1.036E-03	DCF3(4)
D-1	Rn-222+D	9.249E-07	0.000E+00	DCF3(5)
D-1	Th-230	7.770E-04	7.770E-04	DCF3(6)
D-1	Th-234+D	1.259E-05	1.258E-05	DCF3(7)
D-1	U-234	1.813E-04	1.813E-04	DCF3(8)
D-1	U-238	1.665E-04	1.665E-04	DCF3(9)
D-34	Food transfer factors:			
D-34	Bi-210 , plant/soil concentration ratio, dimensionless	1.000E-01	1.000E-01	RTF(1,1)
D-34	Bi-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(1,2)
D-34	Bi-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-04	5.000E-04	RTF(1,3)
D-34				
D-34	Pb-210 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(2,1)
D-34	Pb-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(2,2)
D-34	Pb-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(2,3)
D-34				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(3,1)
D-34	Po-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(3,2)
D-34	Po-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.400E-04	3.400E-04	RTF(3,3)
D-34				
D-34	Ra-226 , plant/soil concentration ratio, dimensionless	4.000E-02	4.000E-02	RTF(4,1)
D-34	Ra-226 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,2)
D-34	Ra-226 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,3)
D-34				
D-34	Rn-222+D , plant/soil concentration ratio, dimensionless	0.000E+00	0.000E+00	RTF(5,1)
D-34	Rn-222+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,2)
D-34	Rn-222+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,3)
D-34				
D-34	Th-230 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(6,1)
D-34	Th-230 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(6,2)
D-34	Th-230 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(6,3)
D-34				
D-34	Th-234+D , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(7,1)
D-34	Th-234+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(7,2)
D-34	Th-234+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	U-234 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(8,1)
D-34	U-234 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(8,2)
D-34	U-234 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(8,3)
D-34				
D-34	U-238 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(9,1)
D-34	U-238 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(9,2)
D-34	U-238 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(9,3)
D-5	Bioaccumulation factors, fresh water, L/kg:			
D-5	Bi-210 , fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Bi-210 , crustacea and mollusks	1.000E+01	1.000E+01	BIOFAC(1,2)
D-5				
D-5	Pb-210 , fish	3.000E+02	3.000E+02	BIOFAC(2,1)
D-5	Pb-210 , crustacea and mollusks	1.000E+02	1.000E+02	BIOFAC(2,2)
D-5				
D-5	Po-210 , fish	1.000E+02	1.000E+02	BIOFAC(3,1)
D-5	Po-210 , crustacea and mollusks	2.000E+04	2.000E+04	BIOFAC(3,2)
D-5				
D-5	Ra-226 , fish	5.000E+01	5.000E+01	BIOFAC(4,1)
D-5	Ra-226 , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(4,2)
D-5				
D-5	Rn-222+D , fish	0.000E+00	0.000E+00	BIOFAC(5,1)
D-5	Rn-222+D , crustacea and mollusks	0.000E+00	0.000E+00	BIOFAC(5,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(6,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(6,2)
D-5				
D-5	Th-234+D , fish	1.000E+02	1.000E+02	BIOFAC(7,1)
D-5	Th-234+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(7,2)
D-5				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-5	U-234 , fish	1.000E+01	1.000E+01	BIOFAC(8,1)
D-5	U-234 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(8,2)
D-5				
D-5	U-238 , fish	1.000E+01	1.000E+01	BIOFAC(9,1)
D-5	U-238 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(9,2)

#For DCF1(xxx) only, factors are for infinite depth & area. See ETFG table in Ground Pathway of Detailed Report.
*Base Case means Default.Lib w/o Associate Nuclide contributions.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.500E+03	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	2.500E-01	2.000E+00	---	THICK0
R011	Fraction of contamination that is submerged	0.000E+00	0.000E+00	---	SUBMFRACT
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	not used	3.000E+00	---	T(3)
R011	Times for calculations (yr)	not used	1.000E+01	---	T(4)
R011	Times for calculations (yr)	not used	3.000E+01	---	T(5)
R011	Times for calculations (yr)	not used	1.000E+02	---	T(6)
R011	Times for calculations (yr)	not used	3.000E+02	---	T(7)
R011	Times for calculations (yr)	not used	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Bi-210	1.350E+01	0.000E+00	---	S1(1)
R012	Initial principal radionuclide (pCi/g): Pb-210	1.350E+01	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Po-210	1.350E+01	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Ra-226	1.350E+01	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Rn-222	1.350E+01	0.000E+00	---	S1(5)
R012	Initial principal radionuclide (pCi/g): Th-230	2.500E+00	0.000E+00	---	S1(6)
R012	Initial principal radionuclide (pCi/g): Th-234	1.500E+00	0.000E+00	---	S1(7)
R012	Initial principal radionuclide (pCi/g): U-234	1.600E+00	0.000E+00	---	S1(8)
R012	Initial principal radionuclide (pCi/g): U-238	1.500E+00	0.000E+00	---	S1(9)
R012	Concentration in groundwater (pCi/L): Bi-210	not used	0.000E+00	---	W1(1)
R012	Concentration in groundwater (pCi/L): Pb-210	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Po-210	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Rn-222	not used	0.000E+00	---	W1(5)
R012	Concentration in groundwater (pCi/L): Th-230	not used	0.000E+00	---	W1(6)
R012	Concentration in groundwater (pCi/L): Th-234	not used	0.000E+00	---	W1(7)
R012	Concentration in groundwater (pCi/L): U-234	not used	0.000E+00	---	W1(8)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(9)
R013	Cover depth (m)	0.000E+00	0.000E+00	---	COVER0
R013	Density of cover material (g/cm**3)	not used	1.500E+00	---	DENSCV
R013	Cover depth erosion rate (m/yr)	not used	1.000E-03	---	VCV
R013	Density of contaminated zone (g/cm**3)	2.250E+00	1.500E+00	---	DENSCZ
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCZ
R013	Contaminated zone total porosity	4.000E-01	4.000E-01	---	TPCZ
R013	Contaminated zone field capacity	2.000E-01	2.000E-01	---	FCCZ
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01	---	HCCZ
R013	Contaminated zone b parameter	5.300E+00	5.300E+00	---	BCZ
R013	Average annual wind speed (m/sec)	2.000E+00	2.000E+00	---	WIND
R013	Humidity in air (g/m**3)	not used	8.000E+00	---	HUMID
R013	Evapotranspiration coefficient	5.000E-01	5.000E-01	---	EVAPTR
R013	Precipitation (m/yr)	1.000E+00	1.000E+00	---	PRECIP
R013	Irrigation (m/yr)	2.000E-01	2.000E-01	---	RI
R013	Irrigation mode	overhead	overhead	---	IDITCH

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R013	Runoff coefficient	2.000E-01	2.000E-01	---	RUNOFF
R013	Watershed area for nearby stream or pond (m**2)	not used	1.000E+06	---	WAREA
R013	Accuracy for water/soil computations	not used	1.000E-03	---	EPS
R014	Density of saturated zone (g/cm**3)	not used	1.500E+00	---	DENSAQ
R014	Saturated zone total porosity	not used	4.000E-01	---	TPSZ
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Bi-210				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)
R016	Distribution coefficients for Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.876E-03	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(3)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(3,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(3)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	8.764E-02	ALEACH(3)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(3)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Ra-226				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(4)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(4,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(4)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.267E-02	ALEACH(4)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(4)
R016	Distribution coefficients for Rn-222				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(5)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(5,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(5)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	6.232E+00	ALEACH(5)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(5)
R016	Distribution coefficients for Th-230				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(6)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(6,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(6)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(6)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(6)
R016	Distribution coefficients for Th-234				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(7)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(7,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(7)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.481E-05	ALEACH(7)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(7)
R016	Distribution coefficients for U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(8)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(8,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(8)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(8)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(8)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.773E-02	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R017	Inhalation rate (m**3/yr)	1.140E+04	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	2.000E-04	1.000E-04	---	MLINH
R017	Exposure duration	1.000E+00	3.000E+01	---	ED
R017	Shielding factor, inhalation	4.000E-01	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	not used	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	0.000E+00	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	1.800E-02	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	not used	1.000E+00	-1 shows non-circular AREA.	FS

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	4.250E+00	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	8.500E+00	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	1.275E+01	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	1.700E+01	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	2.125E+01	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	2.550E+01	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	2.975E+01	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	3.400E+01	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	3.825E+01	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	4.250E+01	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	4.675E+01	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	5.100E+01	0.000E+00	---	RAD_SHAPE(12)
R017	Fractions of annular areas within AREA:				
R017	Ring 1	1.000E+00	1.000E+00	---	FRACA(1)
R017	Ring 2	1.000E+00	2.732E-01	---	FRACA(2)
R017	Ring 3	5.000E-01	0.000E+00	---	FRACA(3)
R017	Ring 4	3.500E-01	0.000E+00	---	FRACA(4)
R017	Ring 5	2.600E-01	0.000E+00	---	FRACA(5)
R017	Ring 6	2.100E-01	0.000E+00	---	FRACA(6)
R017	Ring 7	1.800E-01	0.000E+00	---	FRACA(7)
R017	Ring 8	1.600E-01	0.000E+00	---	FRACA(8)
R017	Ring 9	1.400E-01	0.000E+00	---	FRACA(9)
R017	Ring 10	1.200E-01	0.000E+00	---	FRACA(10)
R017	Ring 11	1.100E-01	0.000E+00	---	FRACA(11)
R017	Ring 12	7.000E-02	0.000E+00	---	FRACA(12)
R018	Fruits, vegetables and grain consumption (kg/yr)	not used	1.600E+02	---	DIET(1)
R018	Leafy vegetable consumption (kg/yr)	not used	1.400E+01	---	DIET(2)
R018	Milk consumption (L/yr)	not used	9.200E+01	---	DIET(3)
R018	Meat and poultry consumption (kg/yr)	not used	6.300E+01	---	DIET(4)
R018	Fish consumption (kg/yr)	not used	5.400E+00	---	DIET(5)
R018	Other seafood consumption (kg/yr)	not used	9.000E-01	---	DIET(6)
R018	Soil ingestion rate (g/yr)	8.250E+01	3.650E+01	---	SOIL
R018	Drinking water intake (L/yr)	not used	5.100E+02	---	DWI
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)
R19B	Translocation Factor for Fodder	not used	1.000E+00	---	TIV(3)
R19B	Dry Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RDRY(1)
R19B	Dry Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RDRY(2)
R19B	Dry Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RDRY(3)
R19B	Wet Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RWET(1)
R19B	Wet Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RWET(2)
R19B	Wet Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RWET(3)
R19B	Weathering Removal Constant for Vegetation	not used	2.000E+01	---	WLAM
C14	C-12 concentration in water (g/cm**3)	not used	2.000E-05	---	C12WTR
C14	C-12 concentration in contaminated soil (g/g)	not used	3.000E-02	---	C12CZ
C14	Fraction of vegetation carbon from soil	not used	2.000E-02	---	CSOIL
C14	Fraction of vegetation carbon from air	not used	9.800E-01	---	CAIR
C14	C-14 evasion layer thickness in soil (m)	not used	3.000E-01	---	DMC
C14	C-14 evasion flux rate from soil (1/sec)	not used	7.000E-07	---	EVSN
C14	C-12 evasion flux rate from soil (1/sec)	not used	1.000E-10	---	REVSN
C14	Fraction of grain in beef cattle feed	not used	8.000E-01	---	AVFG4
C14	Fraction of grain in milk cow feed	not used	2.000E-01	---	AVFG5
STOR	Storage times of contaminated foodstuffs (days):				
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS
TITL	Maximum number of integration points for dose	17	---	---	LYMAX
TITL	Maximum number of integration points for risk	257	---	---	KYMAX

Summary of Pathway Selections

Pathway	User Selection
1 -- external gamma	suppressed
2 -- inhalation (w/o radon)	active
3 -- plant ingestion	suppressed
4 -- meat ingestion	suppressed
5 -- milk ingestion	suppressed
6 -- aquatic foods	suppressed
7 -- drinking water	suppressed
8 -- soil ingestion	active
9 -- radon	suppressed
Find peak pathway doses	suppressed

Summary : Utility Worker - PG in Road Base
File : C:\USERS\NEMICKASH\DESKTOP\FERTILIZER INSTITUTE\RESRAD\UW_RB_071019.RAD

Contaminated Zone Dimensions	
Area:	1500.00 square meters
Thickness:	0.25 meters
Cover Depth:	0.00 meters

Initial Soil Concentrations, pCi/g	
Bi-210	1.350E+01
Pb-210	1.350E+01
Po-210	1.350E+01
Ra-226	1.350E+01
Rn-222	1.350E+01
Th-230	2.500E+00
Th-234	1.500E+00
U-234	1.600E+00
U-238	1.500E+00

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 2.500E+01 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0.000E+00	1.000E+00
TDOSE(t):	1.682E-01	1.612E-01
M(t):	6.726E-03	6.450E-03

Maximum TDOSE(t): 1.682E-01 mrem/yr at t = 0.000E+00 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	1.787E-05	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.255E-03	0.0075
Pb-210	0.000E+00	0.0000	2.143E-03	0.0127	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.051E-02	0.5383
Po-210	0.000E+00	0.0000	5.456E-04	0.0032	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.960E-02	0.2355
Ra-226	0.000E+00	0.0000	2.727E-03	0.0162	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.176E-02	0.1294
Rn-222	0.000E+00	0.0000	1.079E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.840E-05	0.0002
Th-230	0.000E+00	0.0000	5.281E-03	0.0314	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.885E-03	0.0172
Th-234	0.000E+00	0.0000	2.332E-08	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.671E-06	0.0000
U-234	0.000E+00	0.0000	3.149E-04	0.0019	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.270E-04	0.0025
U-238	0.000E+00	0.0000	2.515E-04	0.0015	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.928E-04	0.0023
Total	0.000E+00	0.0000	1.128E-02	0.0671	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.569E-01	0.9329

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.272E-03	0.0076
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	9.265E-02	0.5510
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.015E-02	0.2388
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.448E-02	0.1456
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.948E-05	0.0002
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	8.167E-03	0.0486
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.695E-06	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.419E-04	0.0044
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.443E-04	0.0038
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.682E-01	1.0000

*Sum of all water independent and dependent pathways.

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	2.677E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.943E-04	0.0012
Pb-210	0.000E+00	0.0000	2.457E-03	0.0152	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.158E-01	0.7184
Po-210	0.000E+00	0.0000	8.022E-05	0.0005	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.822E-03	0.0361
Ra-226	0.000E+00	0.0000	2.758E-03	0.0171	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.450E-02	0.1520
Rn-222	0.000E+00	0.0000	1.054E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.967E-05	0.0003
Th-230	0.000E+00	0.0000	5.281E-03	0.0328	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.887E-03	0.0179
Th-234	0.000E+00	0.0000	7.905E-11	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.795E-10	0.0000
U-234	0.000E+00	0.0000	3.094E-04	0.0019	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.195E-04	0.0026
U-238	0.000E+00	0.0000	2.471E-04	0.0015	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.885E-04	0.0024
Total	0.000E+00	0.0000	1.114E-02	0.0691	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.501E-01	0.9309

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.970E-04	0.0012
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.183E-01	0.7337
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.903E-03	0.0366
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.726E-02	0.1691
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	5.072E-05	0.0003
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	8.169E-03	0.0507
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.586E-10	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	7.289E-04	0.0045
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	6.356E-04	0.0039
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.612E-01	1.0000

*Sum of all water independent and dependent pathways.

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	2.119E-07	4.809E-32
Bi-210	Po-210	1.000E+00	9.404E-05	1.459E-05
Bi-210	∑DSR(j)		9.426E-05	1.459E-05
Pb-210	Pb-210	1.000E+00	3.832E-03	3.682E-03
Pb-210	Bi-210	1.000E+00	7.764E-06	7.641E-06
Pb-210	Po-210	1.000E+00	3.023E-03	5.073E-03
Pb-210	∑DSR(j)		6.863E-03	8.763E-03
Po-210	Po-210	1.000E+00	2.974E-03	4.372E-04
Ra-226	Ra-226	1.000E+00	1.728E-03	1.705E-03
Ra-226	Rn-222+D	1.000E+00	1.764E-06	1.780E-06
Ra-226	Pb-210	1.000E+00	5.310E-05	1.585E-04
Ra-226	Bi-210	1.000E+00	1.063E-07	3.249E-07
Ra-226	Po-210	1.000E+00	3.081E-05	1.535E-04
Ra-226	∑DSR(j)		1.814E-03	2.019E-03
Rn-222+D	Rn-222+D	1.000E+00	4.317E-08	1.486E-39
Rn-222+D	Pb-210	1.000E+00	1.609E-06	1.581E-06
Rn-222+D	Bi-210	1.000E+00	3.314E-09	3.280E-09
Rn-222+D	Po-210	1.000E+00	1.269E-06	2.173E-06
Rn-222+D	∑DSR(j)		2.924E-06	3.757E-06
Th-230	Th-230	1.000E+00	3.266E-03	3.266E-03
Th-230	Ra-226	1.000E+00	3.751E-07	1.119E-06
Th-230	Rn-222+D	1.000E+00	3.809E-10	1.157E-09
Th-230	Pb-210	1.000E+00	7.596E-09	5.362E-08
Th-230	Bi-210	1.000E+00	1.494E-11	1.087E-10
Th-230	Po-210	1.000E+00	3.503E-09	4.145E-08
Th-230	∑DSR(j)		3.267E-03	3.267E-03
Th-234+D	Th-234+D	1.000E+00	1.796E-06	4.922E-11
Th-234+D	U-234	1.000E+00	1.133E-10	1.231E-10
Th-234+D	Th-230	1.000E+00	3.266E-15	1.100E-14
Th-234+D	Ra-226	1.000E+00	2.313E-19	1.861E-18
Th-234+D	Rn-222+D	1.000E+00	2.309E-22	1.907E-21
Th-234+D	Pb-210	1.000E+00	3.216E-21	5.829E-20
Th-234+D	Bi-210	1.000E+00	6.185E-24	1.168E-22
Th-234+D	Po-210	1.000E+00	1.158E-21	3.694E-20
Th-234+D	∑DSR(j)		1.797E-06	1.724E-10

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
U-234	U-234	1.000E+00	4.637E-04	4.555E-04	
U-234	Th-230	1.000E+00	1.462E-08	4.350E-08	
U-234	Ra-226	1.000E+00	1.122E-12	7.783E-12	
U-234	Rn-222+D	1.000E+00	1.124E-15	7.982E-15	
U-234	Pb-210	1.000E+00	1.685E-14	2.563E-13	
U-234	Bi-210	1.000E+00	3.259E-17	5.144E-16	
U-234	Po-210	1.000E+00	6.437E-15	1.672E-13	
U-234	∑DSR(j)		4.637E-04	4.556E-04	
U-238	U-238	5.400E-05	2.228E-08	2.189E-08	
U-238	U-238	9.999E-01	4.126E-04	4.053E-04	
U-238	Th-234+D	9.999E-01	1.692E-05	1.839E-05	
U-238	U-234	9.999E-01	5.429E-10	1.815E-09	
U-238	Th-230	9.999E-01	1.052E-14	8.456E-14	
U-238	Ra-226	9.999E-01	5.630E-19	9.934E-18	
U-238	Rn-222+D	9.999E-01	5.543E-22	1.009E-20	
U-238	Pb-210	9.999E-01	6.220E-21	2.400E-19	
U-238	Bi-210	9.999E-01	1.176E-23	4.762E-22	
U-238	Po-210	9.999E-01	1.908E-21	1.324E-19	
U-238	∑DSR(j)		4.295E-04	4.237E-04	

The DSR includes contributions from associated (half-life ≤ 1 day) daughters.

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00
Bi-210	2.652E+05	1.714E+06
Pb-210	3.643E+03	2.853E+03
Po-210	8.406E+03	5.718E+04
Ra-226	1.378E+04	1.238E+04
Rn-222	8.549E+06	6.654E+06
Th-230	7.653E+03	7.651E+03
Th-234	1.392E+07	1.450E+11
U-234	5.391E+04	5.488E+04
U-238	5.821E+04	5.900E+04

Summary : Utility Worker - PG in Road Base
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Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Nuclide (i)	Initial (pCi/g)	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
Bi-210	1.350E+01	0.000E+00	9.426E-05	2.652E+05	9.426E-05	2.652E+05
Pb-210	1.350E+01	1.000E+00	8.763E-03	2.853E+03	6.863E-03	3.643E+03
Po-210	1.350E+01	0.000E+00	2.974E-03	8.406E+03	2.974E-03	8.406E+03
Ra-226	1.350E+01	1.000E+00	2.019E-03	1.238E+04	1.814E-03	1.378E+04
Rn-222	1.350E+01	1.000E+00	3.757E-06	6.654E+06	2.924E-06	8.549E+06
Th-230	2.500E+00	1.000E+00	3.267E-03	7.651E+03	3.267E-03	7.653E+03
Th-234	1.500E+00	0.000E+00	1.797E-06	1.392E+07	1.797E-06	1.392E+07
U-234	1.600E+00	0.000E+00	4.637E-04	5.391E+04	4.637E-04	5.391E+04
U-238	1.500E+00	0.0869 ± 0.0002	4.299E-04	5.815E+04	4.295E-04	5.821E+04

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	2.861E-06	0.000E+00
Bi-210	Pb-210	1.000E+00	1.048E-04	1.032E-04
Bi-210	Ra-226	1.000E+00	1.435E-06	4.386E-06
Bi-210	Rn-222	1.000E+00	4.474E-08	4.428E-08
Bi-210	Th-230	1.000E+00	3.735E-11	2.718E-10
Bi-210	Th-234	1.000E+00	9.278E-24	1.752E-22
Bi-210	U-234	1.000E+00	5.214E-17	8.231E-16
Bi-210	U-238	9.999E-01	1.764E-23	7.143E-22
Bi-210	∑DOSE(j)		1.092E-04	1.076E-04
Po-210	Bi-210	1.000E+00	1.270E-03	1.970E-04
Po-210	Pb-210	1.000E+00	4.081E-02	6.849E-02
Po-210	Po-210	1.000E+00	4.015E-02	5.903E-03
Po-210	Ra-226	1.000E+00	4.159E-04	2.072E-03
Po-210	Rn-222	1.000E+00	1.713E-05	2.934E-05
Po-210	Th-230	1.000E+00	8.757E-09	1.036E-07
Po-210	Th-234	1.000E+00	1.737E-21	5.541E-20
Po-210	U-234	1.000E+00	1.030E-14	2.676E-13
Po-210	U-238	9.999E-01	2.862E-21	1.985E-19
Po-210	∑DOSE(j)		8.266E-02	7.669E-02
Pb-210	Pb-210	1.000E+00	5.174E-02	4.971E-02
Pb-210	Ra-226	1.000E+00	7.169E-04	2.139E-03
Pb-210	Rn-222	1.000E+00	2.172E-05	2.134E-05
Pb-210	Th-230	1.000E+00	1.899E-08	1.340E-07
Pb-210	Th-234	1.000E+00	4.823E-21	8.743E-20
Pb-210	U-234	1.000E+00	2.697E-14	4.101E-13
Pb-210	U-238	9.999E-01	9.330E-21	3.600E-19
Pb-210	∑DOSE(j)		5.248E-02	5.187E-02
Ra-226	Ra-226	1.000E+00	2.333E-02	2.302E-02
Ra-226	Th-230	1.000E+00	9.377E-07	2.797E-06
Ra-226	Th-234	1.000E+00	3.469E-19	2.792E-18
Ra-226	U-234	1.000E+00	1.795E-12	1.245E-11
Ra-226	U-238	9.999E-01	8.446E-19	1.490E-17
Ra-226	∑DOSE(j)		2.333E-02	2.302E-02
Rn-222	Ra-226	1.000E+00	2.382E-05	2.403E-05
Rn-222	Rn-222	1.000E+00	5.828E-07	0.000E+00
Rn-222	Th-230	1.000E+00	9.523E-10	2.892E-09
Rn-222	Th-234	1.000E+00	3.464E-22	2.860E-21
Rn-222	U-234	1.000E+00	1.798E-15	1.277E-14
Rn-222	U-238	9.999E-01	8.315E-22	1.514E-20
Rn-222	∑DOSE(j)		2.440E-05	2.404E-05
Th-230	Th-230	1.000E+00	8.166E-03	8.166E-03
Th-230	Th-234	1.000E+00	4.899E-15	1.650E-14
Th-230	U-234	1.000E+00	2.338E-08	6.960E-08
Th-230	U-238	9.999E-01	1.578E-14	1.268E-13
Th-230	∑DOSE(j)		8.166E-03	8.166E-03

Summary : Utility Worker - PG in Road Base
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Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	2.695E-06	7.382E-11
Th-234	U-238	9.999E-01	2.538E-05	2.758E-05
Th-234	∑DOSE(j)		2.807E-05	2.758E-05
U-234	Th-234	1.000E+00	1.699E-10	1.847E-10
U-234	U-234	1.000E+00	7.419E-04	7.289E-04
U-234	U-238	9.999E-01	8.144E-10	2.723E-09
U-234	∑DOSE(j)		7.419E-04	7.289E-04
U-238	U-238	5.400E-05	3.342E-08	3.283E-08
U-238	U-238	9.999E-01	6.188E-04	6.080E-04
U-238	∑DOSE(j)		6.189E-04	6.080E-04

THF(i) is the thread fraction of the parent nuclide.

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.350E+01	3.063E-24
Bi-210	Pb-210	1.000E+00	0.000E+00	1.155E+01
Bi-210	Ra-226	1.000E+00	0.000E+00	3.223E-01
Bi-210	Rn-222	1.000E+00	0.000E+00	4.960E-03
Bi-210	Th-230	1.000E+00	0.000E+00	1.264E-05
Bi-210	Th-234	1.000E+00	0.000E+00	4.515E-18
Bi-210	U-234	1.000E+00	0.000E+00	2.353E-11
Bi-210	U-238	9.999E-01	0.000E+00	1.067E-17
Bi-210	∑S(j):		1.350E+01	1.188E+01
Po-210	Bi-210	1.000E+00	0.000E+00	6.623E-02
Po-210	Pb-210	1.000E+00	0.000E+00	9.479E+00
Po-210	Po-210	1.000E+00	1.350E+01	1.985E+00
Po-210	Ra-226	1.000E+00	0.000E+00	1.689E-01
Po-210	Rn-222	1.000E+00	0.000E+00	4.049E-03
Po-210	Th-230	1.000E+00	0.000E+00	4.992E-06
Po-210	Th-234	1.000E+00	0.000E+00	1.366E-18
Po-210	U-234	1.000E+00	0.000E+00	7.521E-12
Po-210	U-238	9.999E-01	0.000E+00	2.722E-18
Po-210	∑S(j):		1.350E+01	1.170E+01
Pb-210	Pb-210	1.000E+00	1.350E+01	1.297E+01
Pb-210	Ra-226	1.000E+00	0.000E+00	3.685E-01
Pb-210	Rn-222	1.000E+00	0.000E+00	5.568E-03
Pb-210	Th-230	1.000E+00	0.000E+00	1.471E-05
Pb-210	Th-234	1.000E+00	0.000E+00	5.371E-18
Pb-210	U-234	1.000E+00	0.000E+00	2.786E-11
Pb-210	U-238	9.999E-01	0.000E+00	1.292E-17
Pb-210	∑S(j):		1.350E+01	1.335E+01
Ra-226	Ra-226	1.000E+00	1.350E+01	1.332E+01
Ra-226	Th-230	1.000E+00	0.000E+00	1.076E-03
Ra-226	Th-234	1.000E+00	0.000E+00	6.472E-16
Ra-226	U-234	1.000E+00	0.000E+00	3.088E-09
Ra-226	U-238	9.999E-01	0.000E+00	2.087E-15
Ra-226	∑S(j):		1.350E+01	1.333E+01
Rn-222	Ra-226	1.000E+00	0.000E+00	1.218E+01
Rn-222	Rn-222	1.000E+00	1.350E+01	4.647E-31
Rn-222	Th-230	1.000E+00	0.000E+00	9.699E-04
Rn-222	Th-234	1.000E+00	0.000E+00	5.740E-16
Rn-222	U-234	1.000E+00	0.000E+00	2.746E-09
Rn-222	U-238	9.999E-01	0.000E+00	1.825E-15
Rn-222	∑S(j):		1.350E+01	1.218E+01
Th-230	Th-230	1.000E+00	2.500E+00	2.500E+00
Th-230	Th-234	1.000E+00	0.000E+00	3.270E-12
Th-230	U-234	1.000E+00	0.000E+00	1.428E-05
Th-230	U-238	9.999E-01	0.000E+00	1.567E-11
Th-230	∑S(j):		2.500E+00	2.500E+00

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.500E+00	4.110E-05
Th-234	U-238	9.999E-01	0.000E+00	1.476E+00
Th-234	∑S(j):		1.500E+00	1.476E+00
U-234	Th-234	1.000E+00	0.000E+00	3.983E-07
U-234	U-234	1.000E+00	1.600E+00	1.572E+00
U-234	U-238	9.999E-01	0.000E+00	3.786E-06
U-234	∑S(j):		1.600E+00	1.572E+00
U-238	U-238	5.400E-05	8.100E-05	7.958E-05
U-238	U-238	9.999E-01	1.500E+00	1.474E+00
U-238	∑S(j):		1.500E+00	1.474E+00

THF(i) is the thread fraction of the parent nuclide.

RESCALC.EXE execution time = 18.59 seconds

RESRAD Modelling Results

Reclaimer Resident

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Dose Conversion Factor (and Related) Parameter Summary
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
A-1	DCF's for external ground radiation, (mrem/yr)/(pCi/g)			
A-1	At-218 (Source: ICRP 60)	4.878E-03	4.878E-03	DCF1(1)
A-1	Bi-210 (Source: ICRP 60)	5.476E-03	5.476E-03	DCF1(2)
A-1	Bi-214 (Source: ICRP 60)	9.325E+00	9.325E+00	DCF1(3)
A-1	Pa-234 (Source: ICRP 60)	1.088E+01	1.088E+01	DCF1(4)
A-1	Pa-234m (Source: ICRP 60)	9.867E-02	9.867E-02	DCF1(5)
A-1	Pb-210 (Source: ICRP 60)	1.981E-03	1.981E-03	DCF1(6)
A-1	Pb-214 (Source: ICRP 60)	1.243E+00	1.243E+00	DCF1(7)
A-1	Po-210 (Source: ICRP 60)	4.934E-05	4.934E-05	DCF1(8)
A-1	Po-214 (Source: ICRP 60)	4.840E-04	4.840E-04	DCF1(9)
A-1	Po-218 (Source: ICRP 60)	5.326E-05	5.326E-05	DCF1(10)
A-1	Ra-226 (Source: ICRP 60)	2.915E-02	2.915E-02	DCF1(11)
A-1	Rn-222 (Source: ICRP 60)	2.186E-03	2.186E-03	DCF1(12)
A-1	Th-230 (Source: ICRP 60)	1.071E-03	1.071E-03	DCF1(13)
A-1	Th-234 (Source: ICRP 60)	2.130E-02	2.130E-02	DCF1(14)
A-1	Tl-210 (Source: ICRP 60)	1.661E+01	1.661E+01	DCF1(15)
A-1	U-234 (Source: ICRP 60)	3.439E-04	3.439E-04	DCF1(16)
A-1	U-238 (Source: ICRP 60)	7.961E-05	7.961E-05	DCF1(17)
B-1	Dose conversion factors for inhalation, mrem/pCi:			
B-1	Bi-210	3.441E-04	3.441E-04	DCF2(1)
B-1	Pb-210	2.072E-02	2.072E-02	DCF2(2)
B-1	Po-210	1.591E-02	1.591E-02	DCF2(3)
B-1	Ra-226	3.515E-02	3.515E-02	DCF2(4)
B-1	Rn-222+D	1.073E-04	0.000E+00	DCF2(5)
B-1	Th-230	3.700E-01	3.700E-01	DCF2(6)
B-1	Th-234+D	2.849E-05	2.849E-05	DCF2(7)
B-1	U-234	3.478E-02	3.478E-02	DCF2(8)
B-1	U-238	2.960E-02	2.960E-02	DCF2(9)
D-1	Dose conversion factors for ingestion, mrem/pCi:			
D-1	Bi-210	4.810E-06	4.810E-06	DCF3(1)
D-1	Pb-210	2.553E-03	2.553E-03	DCF3(2)
D-1	Po-210	4.440E-03	4.440E-03	DCF3(3)
D-1	Ra-226	1.036E-03	1.036E-03	DCF3(4)
D-1	Rn-222+D	9.249E-07	0.000E+00	DCF3(5)
D-1	Th-230	7.770E-04	7.770E-04	DCF3(6)
D-1	Th-234+D	1.259E-05	1.258E-05	DCF3(7)
D-1	U-234	1.813E-04	1.813E-04	DCF3(8)
D-1	U-238	1.665E-04	1.665E-04	DCF3(9)
D-34	Food transfer factors:			
D-34	Bi-210 , plant/soil concentration ratio, dimensionless	1.000E-01	1.000E-01	RTF(1,1)
D-34	Bi-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	2.000E-03	2.000E-03	RTF(1,2)
D-34	Bi-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-04	5.000E-04	RTF(1,3)
D-34				
D-34	Pb-210 , plant/soil concentration ratio, dimensionless	1.000E-02	1.000E-02	RTF(2,1)
D-34	Pb-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	8.000E-04	8.000E-04	RTF(2,2)
D-34	Pb-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.000E-04	3.000E-04	RTF(2,3)
D-34				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-34	Po-210 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(3,1)
D-34	Po-210 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	5.000E-03	5.000E-03	RTF(3,2)
D-34	Po-210 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	3.400E-04	3.400E-04	RTF(3,3)
D-34				
D-34	Ra-226 , plant/soil concentration ratio, dimensionless	4.000E-02	4.000E-02	RTF(4,1)
D-34	Ra-226 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,2)
D-34	Ra-226 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	1.000E-03	1.000E-03	RTF(4,3)
D-34				
D-34	Rn-222+D , plant/soil concentration ratio, dimensionless	0.000E+00	0.000E+00	RTF(5,1)
D-34	Rn-222+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,2)
D-34	Rn-222+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	0.000E+00	0.000E+00	RTF(5,3)
D-34				
D-34	Th-230 , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(6,1)
D-34	Th-230 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(6,2)
D-34	Th-230 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(6,3)
D-34				
D-34	Th-234+D , plant/soil concentration ratio, dimensionless	1.000E-03	1.000E-03	RTF(7,1)
D-34	Th-234+D , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	1.000E-04	1.000E-04	RTF(7,2)
D-34	Th-234+D , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	5.000E-06	5.000E-06	RTF(7,3)
D-34				
D-34	U-234 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(8,1)
D-34	U-234 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(8,2)
D-34	U-234 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(8,3)
D-34				
D-34	U-238 , plant/soil concentration ratio, dimensionless	2.500E-03	2.500E-03	RTF(9,1)
D-34	U-238 , beef/livestock-intake ratio, (pCi/kg)/(pCi/d)	3.400E-04	3.400E-04	RTF(9,2)
D-34	U-238 , milk/livestock-intake ratio, (pCi/L)/(pCi/d)	6.000E-04	6.000E-04	RTF(9,3)
D-5	Bioaccumulation factors, fresh water, L/kg:			
D-5	Bi-210 , fish	1.500E+01	1.500E+01	BIOFAC(1,1)
D-5	Bi-210 , crustacea and mollusks	1.000E+01	1.000E+01	BIOFAC(1,2)
D-5				
D-5	Pb-210 , fish	3.000E+02	3.000E+02	BIOFAC(2,1)
D-5	Pb-210 , crustacea and mollusks	1.000E+02	1.000E+02	BIOFAC(2,2)
D-5				
D-5	Po-210 , fish	1.000E+02	1.000E+02	BIOFAC(3,1)
D-5	Po-210 , crustacea and mollusks	2.000E+04	2.000E+04	BIOFAC(3,2)
D-5				
D-5	Ra-226 , fish	5.000E+01	5.000E+01	BIOFAC(4,1)
D-5	Ra-226 , crustacea and mollusks	2.500E+02	2.500E+02	BIOFAC(4,2)
D-5				
D-5	Rn-222+D , fish	0.000E+00	0.000E+00	BIOFAC(5,1)
D-5	Rn-222+D , crustacea and mollusks	0.000E+00	0.000E+00	BIOFAC(5,2)
D-5				
D-5	Th-230 , fish	1.000E+02	1.000E+02	BIOFAC(6,1)
D-5	Th-230 , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(6,2)
D-5				
D-5	Th-234+D , fish	1.000E+02	1.000E+02	BIOFAC(7,1)
D-5	Th-234+D , crustacea and mollusks	5.000E+02	5.000E+02	BIOFAC(7,2)
D-5				

Dose Conversion Factor (and Related) Parameter Summary (continued)
Dose Library: ICRP 72 (Adult)

Menu	Parameter	Current Value#	Base Case*	Parameter Name
D-5	U-234 , fish	1.000E+01	1.000E+01	BIOFAC(8,1)
D-5	U-234 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(8,2)
D-5				
D-5	U-238 , fish	1.000E+01	1.000E+01	BIOFAC(9,1)
D-5	U-238 , crustacea and mollusks	6.000E+01	6.000E+01	BIOFAC(9,2)

#For DCF1(xxx) only, factors are for infinite depth & area. See ETFG table in Ground Pathway of Detailed Report.
*Base Case means Default.Lib w/o Associate Nuclide contributions.

Site-Specific Parameter Summary

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R011	Area of contaminated zone (m**2)	1.000E+02	1.000E+04	---	AREA
R011	Thickness of contaminated zone (m)	1.000E-01	2.000E+00	---	THICK0
R011	Fraction of contamination that is submerged	0.000E+00	0.000E+00	---	SUBMFRACT
R011	Length parallel to aquifer flow (m)	not used	1.000E+02	---	LCZPAQ
R011	Basic radiation dose limit (mrem/yr)	2.500E+01	3.000E+01	---	BRDL
R011	Time since placement of material (yr)	0.000E+00	0.000E+00	---	TI
R011	Times for calculations (yr)	1.000E+00	1.000E+00	---	T(2)
R011	Times for calculations (yr)	not used	3.000E+00	---	T(3)
R011	Times for calculations (yr)	not used	1.000E+01	---	T(4)
R011	Times for calculations (yr)	not used	3.000E+01	---	T(5)
R011	Times for calculations (yr)	not used	1.000E+02	---	T(6)
R011	Times for calculations (yr)	not used	3.000E+02	---	T(7)
R011	Times for calculations (yr)	not used	1.000E+03	---	T(8)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(9)
R011	Times for calculations (yr)	not used	0.000E+00	---	T(10)
R012	Initial principal radionuclide (pCi/g): Bi-210	1.000E+01	0.000E+00	---	S1(1)
R012	Initial principal radionuclide (pCi/g): Pb-210	1.000E+01	0.000E+00	---	S1(2)
R012	Initial principal radionuclide (pCi/g): Po-210	1.000E+01	0.000E+00	---	S1(3)
R012	Initial principal radionuclide (pCi/g): Ra-226	1.000E+01	0.000E+00	---	S1(4)
R012	Initial principal radionuclide (pCi/g): Rn-222	1.000E+01	0.000E+00	---	S1(5)
R012	Initial principal radionuclide (pCi/g): Th-230	1.800E+00	0.000E+00	---	S1(6)
R012	Initial principal radionuclide (pCi/g): Th-234	1.100E+00	0.000E+00	---	S1(7)
R012	Initial principal radionuclide (pCi/g): U-234	1.200E+00	0.000E+00	---	S1(8)
R012	Initial principal radionuclide (pCi/g): U-238	1.100E+00	0.000E+00	---	S1(9)
R012	Concentration in groundwater (pCi/L): Bi-210	not used	0.000E+00	---	W1(1)
R012	Concentration in groundwater (pCi/L): Pb-210	not used	0.000E+00	---	W1(2)
R012	Concentration in groundwater (pCi/L): Po-210	not used	0.000E+00	---	W1(3)
R012	Concentration in groundwater (pCi/L): Ra-226	not used	0.000E+00	---	W1(4)
R012	Concentration in groundwater (pCi/L): Rn-222	not used	0.000E+00	---	W1(5)
R012	Concentration in groundwater (pCi/L): Th-230	not used	0.000E+00	---	W1(6)
R012	Concentration in groundwater (pCi/L): Th-234	not used	0.000E+00	---	W1(7)
R012	Concentration in groundwater (pCi/L): U-234	not used	0.000E+00	---	W1(8)
R012	Concentration in groundwater (pCi/L): U-238	not used	0.000E+00	---	W1(9)
R013	Cover depth (m)	2.000E-01	0.000E+00	---	COVER0
R013	Density of cover material (g/cm**3)	2.250E+00	1.500E+00	---	DENSCV
R013	Cover depth erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCV
R013	Density of contaminated zone (g/cm**3)	2.250E+00	1.500E+00	---	DENSCZ
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	1.000E-03	---	VCZ
R013	Contaminated zone total porosity	4.000E-01	4.000E-01	---	TPCZ
R013	Contaminated zone field capacity	2.000E-01	2.000E-01	---	FCCZ
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01	---	HCCZ
R013	Contaminated zone b parameter	5.300E+00	5.300E+00	---	BCZ
R013	Average annual wind speed (m/sec)	2.000E+00	2.000E+00	---	WIND
R013	Humidity in air (g/m**3)	not used	8.000E+00	---	HUMID
R013	Evapotranspiration coefficient	5.000E-01	5.000E-01	---	EVAPTR
R013	Precipitation (m/yr)	1.000E+00	1.000E+00	---	PRECIP
R013	Irrigation (m/yr)	2.000E-01	2.000E-01	---	RI
R013	Irrigation mode	overhead	overhead	---	IDITCH

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R013	Runoff coefficient	2.000E-01	2.000E-01	---	RUNOFF
R013	Watershed area for nearby stream or pond (m**2)	not used	1.000E+06	---	WAREA
R013	Accuracy for water/soil computations	not used	1.000E-03	---	EPS
R014	Density of saturated zone (g/cm**3)	not used	1.500E+00	---	DENSAQ
R014	Saturated zone total porosity	not used	4.000E-01	---	TPSZ
R014	Saturated zone effective porosity	not used	2.000E-01	---	EPSZ
R014	Saturated zone field capacity	not used	2.000E-01	---	FCSZ
R014	Saturated zone hydraulic conductivity (m/yr)	not used	1.000E+02	---	HCSZ
R014	Saturated zone hydraulic gradient	not used	2.000E-02	---	HGWT
R014	Saturated zone b parameter	not used	5.300E+00	---	BSZ
R014	Water table drop rate (m/yr)	not used	1.000E-03	---	VWT
R014	Well pump intake depth (m below water table)	not used	1.000E+01	---	DWIBWT
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	not used	ND	---	MODEL
R014	Well pumping rate (m**3/yr)	not used	2.500E+02	---	UW
R015	Number of unsaturated zone strata	not used	1	---	NS
R015	Unsat. zone 1, thickness (m)	not used	4.000E+00	---	H(1)
R015	Unsat. zone 1, soil density (g/cm**3)	not used	1.500E+00	---	DENSUZ(1)
R015	Unsat. zone 1, total porosity	not used	4.000E-01	---	TPUZ(1)
R015	Unsat. zone 1, effective porosity	not used	2.000E-01	---	EPUZ(1)
R015	Unsat. zone 1, field capacity	not used	2.000E-01	---	FCUZ(1)
R015	Unsat. zone 1, soil-specific b parameter	not used	5.300E+00	---	BUZ(1)
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	not used	1.000E+01	---	HCUZ(1)
R016	Distribution coefficients for Bi-210				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(1)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(1,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(1)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.558E+01	ALEACH(1)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(1)
R016	Distribution coefficients for Pb-210				
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02	---	DCNUCC(2)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+02	---	DCNUCU(2,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+02	---	DCNUCS(2)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	2.219E-02	ALEACH(2)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(2)
R016	Distribution coefficients for Po-210				
R016	Contaminated zone (cm**3/g)	1.000E+01	1.000E+01	---	DCNUCC(3)
R016	Unsaturated zone 1 (cm**3/g)	not used	1.000E+01	---	DCNUCU(3,1)
R016	Saturated zone (cm**3/g)	not used	1.000E+01	---	DCNUCS(3)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	2.191E-01	ALEACH(3)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(3)

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R016	Distribution coefficients for Ra-226				
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01	---	DCNUCC(4)
R016	Unsaturated zone 1 (cm**3/g)	not used	7.000E+01	---	DCNUCU(4,1)
R016	Saturated zone (cm**3/g)	not used	7.000E+01	---	DCNUCS(4)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.168E-02	ALEACH(4)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(4)
R016	Distribution coefficients for Rn-222				
R016	Contaminated zone (cm**3/g)	0.000E+00	0.000E+00	---	DCNUCC(5)
R016	Unsaturated zone 1 (cm**3/g)	not used	0.000E+00	---	DCNUCU(5,1)
R016	Saturated zone (cm**3/g)	not used	0.000E+00	---	DCNUCS(5)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	1.558E+01	ALEACH(5)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(5)
R016	Distribution coefficients for Th-230				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(6)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(6,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(6)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.704E-05	ALEACH(6)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(6)
R016	Distribution coefficients for Th-234				
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04	---	DCNUCC(7)
R016	Unsaturated zone 1 (cm**3/g)	not used	6.000E+04	---	DCNUCU(7,1)
R016	Saturated zone (cm**3/g)	not used	6.000E+04	---	DCNUCS(7)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	3.704E-05	ALEACH(7)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(7)
R016	Distribution coefficients for U-234				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(8)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(8,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(8)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	4.432E-02	ALEACH(8)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(8)
R016	Distribution coefficients for U-238				
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01	---	DCNUCC(9)
R016	Unsaturated zone 1 (cm**3/g)	not used	5.000E+01	---	DCNUCU(9,1)
R016	Saturated zone (cm**3/g)	not used	5.000E+01	---	DCNUCS(9)
R016	Leach rate (/yr)	0.000E+00	0.000E+00	4.432E-02	ALEACH(9)
R016	Solubility constant	0.000E+00	0.000E+00	not used	SOLUBK(9)
R017	Inhalation rate (m**3/yr)	not used	8.400E+03	---	INHALR
R017	Mass loading for inhalation (g/m**3)	not used	1.000E-04	---	MLINH
R017	Exposure duration	1.000E+00	3.000E+01	---	ED
R017	Shielding factor, inhalation	not used	4.000E-01	---	SHF3
R017	Shielding factor, external gamma	1.000E+00	7.000E-01	---	SHF1
R017	Fraction of time spent indoors	7.500E-01	5.000E-01	---	FIND
R017	Fraction of time spent outdoors (on site)	0.000E+00	2.500E-01	---	FOTD
R017	Shape factor flag, external gamma	-1.000E+00	1.000E+00	-1 shows non-circular AREA.	FS

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R017	Radii of shape factor array (used if FS = -1):				
R017	Outer annular radius (m), ring 1:	1.167E+00	5.000E+01	---	RAD_SHAPE(1)
R017	Outer annular radius (m), ring 2:	2.333E+00	7.071E+01	---	RAD_SHAPE(2)
R017	Outer annular radius (m), ring 3:	3.500E+00	0.000E+00	---	RAD_SHAPE(3)
R017	Outer annular radius (m), ring 4:	4.667E+00	0.000E+00	---	RAD_SHAPE(4)
R017	Outer annular radius (m), ring 5:	5.833E+00	0.000E+00	---	RAD_SHAPE(5)
R017	Outer annular radius (m), ring 6:	7.000E+00	0.000E+00	---	RAD_SHAPE(6)
R017	Outer annular radius (m), ring 7:	8.167E+00	0.000E+00	---	RAD_SHAPE(7)
R017	Outer annular radius (m), ring 8:	9.333E+00	0.000E+00	---	RAD_SHAPE(8)
R017	Outer annular radius (m), ring 9:	1.050E+01	0.000E+00	---	RAD_SHAPE(9)
R017	Outer annular radius (m), ring 10:	1.167E+01	0.000E+00	---	RAD_SHAPE(10)
R017	Outer annular radius (m), ring 11:	1.283E+01	0.000E+00	---	RAD_SHAPE(11)
R017	Outer annular radius (m), ring 12:	1.400E+01	0.000E+00	---	RAD_SHAPE(12)
R017	Fractions of annular areas within AREA:				
R017	Ring 1	1.000E+00	1.000E+00	---	FRACA(1)
R017	Ring 2	1.000E+00	2.732E-01	---	FRACA(2)
R017	Ring 3	5.000E-01	0.000E+00	---	FRACA(3)
R017	Ring 4	3.200E-01	0.000E+00	---	FRACA(4)
R017	Ring 5	2.400E-01	0.000E+00	---	FRACA(5)
R017	Ring 6	2.000E-01	0.000E+00	---	FRACA(6)
R017	Ring 7	1.600E-01	0.000E+00	---	FRACA(7)
R017	Ring 8	1.400E-01	0.000E+00	---	FRACA(8)
R017	Ring 9	1.200E-01	0.000E+00	---	FRACA(9)
R017	Ring 10	1.100E-01	0.000E+00	---	FRACA(10)
R017	Ring 11	1.000E-01	0.000E+00	---	FRACA(11)
R017	Ring 12	3.700E-02	0.000E+00	---	FRACA(12)
R018	Fruits, vegetables and grain consumption (kg/yr)	not used	1.600E+02	---	DIET(1)
R018	Leafy vegetable consumption (kg/yr)	not used	1.400E+01	---	DIET(2)
R018	Milk consumption (L/yr)	not used	9.200E+01	---	DIET(3)
R018	Meat and poultry consumption (kg/yr)	not used	6.300E+01	---	DIET(4)
R018	Fish consumption (kg/yr)	not used	5.400E+00	---	DIET(5)
R018	Other seafood consumption (kg/yr)	not used	9.000E-01	---	DIET(6)
R018	Soil ingestion rate (g/yr)	not used	3.650E+01	---	SOIL
R018	Drinking water intake (L/yr)	not used	5.100E+02	---	DWI
R018	Contamination fraction of drinking water	not used	1.000E+00	---	FDW
R018	Contamination fraction of household water	not used	1.000E+00	---	FHHW
R018	Contamination fraction of livestock water	not used	1.000E+00	---	FLW
R018	Contamination fraction of irrigation water	not used	1.000E+00	---	FIRW
R018	Contamination fraction of aquatic food	not used	5.000E-01	---	FR9
R018	Contamination fraction of plant food	not used	-1	---	FPLANT
R018	Contamination fraction of meat	not used	-1	---	FMEAT
R018	Contamination fraction of milk	not used	-1	---	FMILK
R019	Livestock fodder intake for meat (kg/day)	not used	6.800E+01	---	LFI5
R019	Livestock fodder intake for milk (kg/day)	not used	5.500E+01	---	LFI6
R019	Livestock water intake for meat (L/day)	not used	5.000E+01	---	LWI5
R019	Livestock water intake for milk (L/day)	not used	1.600E+02	---	LWI6
R019	Livestock soil intake (kg/day)	not used	5.000E-01	---	LSI

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R019	Mass loading for foliar deposition (g/m**3)	not used	1.000E-04	---	MLFD
R019	Depth of soil mixing layer (m)	not used	1.500E-01	---	DM
R019	Depth of roots (m)	not used	9.000E-01	---	DROOT
R019	Drinking water fraction from ground water	not used	1.000E+00	---	FGWDW
R019	Household water fraction from ground water	not used	1.000E+00	---	FGWHH
R019	Livestock water fraction from ground water	not used	1.000E+00	---	FGWLW
R019	Irrigation fraction from ground water	not used	1.000E+00	---	FGWIR
R19B	Wet weight crop yield for Non-Leafy (kg/m**2)	not used	7.000E-01	---	YV(1)
R19B	Wet weight crop yield for Leafy (kg/m**2)	not used	1.500E+00	---	YV(2)
R19B	Wet weight crop yield for Fodder (kg/m**2)	not used	1.100E+00	---	YV(3)
R19B	Growing Season for Non-Leafy (years)	not used	1.700E-01	---	TE(1)
R19B	Growing Season for Leafy (years)	not used	2.500E-01	---	TE(2)
R19B	Growing Season for Fodder (years)	not used	8.000E-02	---	TE(3)
R19B	Translocation Factor for Non-Leafy	not used	1.000E-01	---	TIV(1)
R19B	Translocation Factor for Leafy	not used	1.000E+00	---	TIV(2)
R19B	Translocation Factor for Fodder	not used	1.000E+00	---	TIV(3)
R19B	Dry Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RDRY(1)
R19B	Dry Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RDRY(2)
R19B	Dry Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RDRY(3)
R19B	Wet Foliar Interception Fraction for Non-Leafy	not used	2.500E-01	---	RWET(1)
R19B	Wet Foliar Interception Fraction for Leafy	not used	2.500E-01	---	RWET(2)
R19B	Wet Foliar Interception Fraction for Fodder	not used	2.500E-01	---	RWET(3)
R19B	Weathering Removal Constant for Vegetation	not used	2.000E+01	---	WLAM
C14	C-12 concentration in water (g/cm**3)	not used	2.000E-05	---	C12WTR
C14	C-12 concentration in contaminated soil (g/g)	not used	3.000E-02	---	C12CZ
C14	Fraction of vegetation carbon from soil	not used	2.000E-02	---	CSOIL
C14	Fraction of vegetation carbon from air	not used	9.800E-01	---	CAIR
C14	C-14 evasion layer thickness in soil (m)	not used	3.000E-01	---	DMC
C14	C-14 evasion flux rate from soil (1/sec)	not used	7.000E-07	---	EVSN
C14	C-12 evasion flux rate from soil (1/sec)	not used	1.000E-10	---	REVSN
C14	Fraction of grain in beef cattle feed	not used	8.000E-01	---	AVFG4
C14	Fraction of grain in milk cow feed	not used	2.000E-01	---	AVFG5
STOR	Storage times of contaminated foodstuffs (days):				
STOR	Fruits, non-leafy vegetables, and grain	1.400E+01	1.400E+01	---	STOR_T(1)
STOR	Leafy vegetables	1.000E+00	1.000E+00	---	STOR_T(2)
STOR	Milk	1.000E+00	1.000E+00	---	STOR_T(3)
STOR	Meat and poultry	2.000E+01	2.000E+01	---	STOR_T(4)
STOR	Fish	7.000E+00	7.000E+00	---	STOR_T(5)
STOR	Crustacea and mollusks	7.000E+00	7.000E+00	---	STOR_T(6)
STOR	Well water	1.000E+00	1.000E+00	---	STOR_T(7)
STOR	Surface water	1.000E+00	1.000E+00	---	STOR_T(8)
STOR	Livestock fodder	4.500E+01	4.500E+01	---	STOR_T(9)
R021	Thickness of building foundation (m)	not used	1.500E-01	---	FLOOR1
R021	Bulk density of building foundation (g/cm**3)	not used	2.400E+00	---	DENSFL
R021	Total porosity of the cover material	not used	4.000E-01	---	TPCV
R021	Total porosity of the building foundation	not used	1.000E-01	---	TPFL

Site-Specific Parameter Summary (continued)

Menu	Parameter	User Input	Default	Used by RESRAD (If different from user input)	Parameter Name
R021	Volumetric water content of the cover material	not used	5.000E-02	---	PH2OCV
R021	Volumetric water content of the foundation	not used	3.000E-02	---	PH2OFL
R021	Diffusion coefficient for radon gas (m/sec):				
R021	in cover material	not used	2.000E-06	---	DIFCV
R021	in foundation material	not used	3.000E-07	---	DIFFL
R021	in contaminated zone soil	not used	2.000E-06	---	DIFCZ
R021	Radon vertical dimension of mixing (m)	not used	2.000E+00	---	HMIX
R021	Average building air exchange rate (1/hr)	not used	5.000E-01	---	REXG
R021	Height of the building (room) (m)	not used	2.500E+00	---	HRM
R021	Building interior area factor	not used	0.000E+00	---	FAI
R021	Building depth below ground surface (m)	not used	-1.000E+00	---	DMFL
R021	Emanating power of Rn-222 gas	not used	2.500E-01	---	EMANA(1)
R021	Emanating power of Rn-220 gas	not used	1.500E-01	---	EMANA(2)
TITL	Number of graphical time points	32	---	---	NPTS
TITL	Maximum number of integration points for dose	17	---	---	LYMAX
TITL	Maximum number of integration points for risk	257	---	---	KYMAX

Summary of Pathway Selections

Pathway	User Selection
1 -- external gamma	active
2 -- inhalation (w/o radon)	suppressed
3 -- plant ingestion	suppressed
4 -- meat ingestion	suppressed
5 -- milk ingestion	suppressed
6 -- aquatic foods	suppressed
7 -- drinking water	suppressed
8 -- soil ingestion	suppressed
9 -- radon	suppressed
Find peak pathway doses	suppressed

Summary : Reclaimer Resident - PG in Road Base (Center)
File : C:\USERS\NEMICKASH\DESKTOP\FERTILIZER INSTITUTE\RESRAD\RR_RB_CENTER_INDOOR.RAD

Contaminated Zone Dimensions		Initial Soil Concentrations, pCi/g	
Area:	100.00 square meters	Bi-210	1.000E+01
Thickness:	0.10 meters	Pb-210	1.000E+01
Cover Depth:	0.20 meters	Po-210	1.000E+01
		Ra-226	1.000E+01
		Rn-222	1.000E+01
		Th-230	1.800E+00
		Th-234	1.100E+00
		U-234	1.200E+00
		U-238	1.100E+00

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 2.500E+01 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0.000E+00	1.000E+00
TDOSE(t):	1.275E+00	1.228E+00
M(t):	5.098E-02	4.913E-02

Maximum TDOSE(t): 1.275E+00 mrem/yr at t = 0.000E+00 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	1.072E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Pb-210	3.518E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Po-210	2.293E-06	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Ra-226	1.239E+00	0.9723	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Rn-222	3.390E-02	0.0266	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Th-230	4.872E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Th-234	1.295E-04	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
U-234	3.184E-08	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
U-238	1.205E-03	0.0009	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Total	1.275E+00	1.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.072E-06	0.0000
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.518E-05	0.0000
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.293E-06	0.0000
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.239E+00	0.9723
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.390E-02	0.0266
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	4.872E-05	0.0000
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.295E-04	0.0001
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.184E-08	0.0000
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.205E-03	0.0009
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.275E+00	1.0000

*Sum of all water independent and dependent pathways.

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	8.442E-09	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Pb-210	3.544E-05	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Po-210	2.955E-07	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Ra-226	1.227E+00	0.9988	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Rn-222	1.347E-08	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Th-230	1.459E-04	0.0001	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Th-234	3.549E-09	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
U-234	3.104E-08	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
U-238	1.277E-03	0.0010	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000
Total	1.228E+00	1.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 1.000E+00 years

Water Dependent Pathways

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
Nuclide	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Bi-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	8.442E-09	0.0000
Pb-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.544E-05	0.0000
Po-210	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	2.955E-07	0.0000
Ra-226	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.227E+00	0.9988
Rn-222	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.347E-08	0.0000
Th-230	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.459E-04	0.0001
Th-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.549E-09	0.0000
U-234	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	3.104E-08	0.0000
U-238	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.277E-03	0.0010
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	1.228E+00	1.0000

*Sum of all water independent and dependent pathways.

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00	(mrem/yr)/(pCi/g)
Bi-210	Bi-210	1.000E+00	1.010E-07	1.997E-36	
Bi-210	Po-210	1.000E+00	6.207E-09	8.442E-10	
Bi-210	∑DSR(j)		1.072E-07	8.442E-10	
Pb-210	Pb-210	1.000E+00	8.571E-15	8.126E-15	
Pb-210	Bi-210	1.000E+00	3.315E-06	3.216E-06	
Pb-210	Po-210	1.000E+00	2.027E-07	3.277E-07	
Pb-210	∑DSR(j)		3.518E-06	3.544E-06	
Po-210	Po-210	1.000E+00	2.293E-07	2.955E-08	
Ra-226	Ra-226	1.000E+00	4.224E-05	4.090E-05	
Ra-226	Rn-222+D	1.000E+00	1.239E-01	1.226E-01	
Ra-226	Pb-210	1.000E+00	1.051E-16	3.085E-16	
Ra-226	Bi-210	1.000E+00	4.032E-08	1.208E-07	
Ra-226	Po-210	1.000E+00	1.849E-09	8.893E-09	
Ra-226	∑DSR(j)		1.239E-01	1.227E-01	
Rn-222+D	Rn-222+D	1.000E+00	3.390E-03	1.017E-38	
Rn-222+D	Pb-210	1.000E+00	3.188E-18	3.090E-18	
Rn-222+D	Bi-210	1.000E+00	1.256E-09	1.223E-09	
Rn-222+D	Po-210	1.000E+00	7.560E-11	1.244E-10	
Rn-222+D	∑DSR(j)		3.390E-03	1.347E-09	
Th-230	Th-230	1.000E+00	1.503E-07	1.503E-07	
Th-230	Ra-226	1.000E+00	9.197E-09	2.720E-08	
Th-230	Rn-222+D	1.000E+00	2.691E-05	8.088E-05	
Th-230	Pb-210	1.000E+00	1.510E-20	1.053E-19	
Th-230	Bi-210	1.000E+00	5.706E-12	4.085E-11	
Th-230	Po-210	1.000E+00	2.123E-13	2.439E-12	
Th-230	∑DSR(j)		2.707E-05	8.106E-05	
Th-234+D	Th-234+D	1.000E+00	1.178E-04	3.226E-09	
Th-234+D	U-234	1.000E+00	6.471E-15	6.859E-15	
Th-234+D	Th-230	1.000E+00	1.491E-19	4.965E-19	
Th-234+D	Ra-226	1.000E+00	5.647E-21	4.488E-20	
Th-234+D	Rn-222+D	1.000E+00	1.627E-17	1.323E-16	
Th-234+D	Pb-210	1.000E+00	6.384E-33	1.139E-31	
Th-234+D	Bi-210	1.000E+00	2.367E-24	4.375E-23	
Th-234+D	Po-210	1.000E+00	7.063E-26	2.179E-24	
Th-234+D	∑DSR(j)		1.178E-04	3.226E-09	

Dose/Source Ratios Summed Over All Pathways
Parent and Progeny Principal Radionuclide Contributions Indicated

Parent (i)	Product (j)	Thread Fraction	DSR(j,t) At Time in Years 0.000E+00	1.000E+00 (mrem/yr)/(pCi/g)
U-234	U-234	1.000E+00	2.645E-08	2.531E-08
U-234	Th-230	1.000E+00	6.665E-13	1.961E-12
U-234	Ra-226	1.000E+00	2.737E-14	1.874E-13
U-234	Rn-222+D	1.000E+00	7.910E-11	5.532E-10
U-234	Pb-210	1.000E+00	3.342E-26	5.004E-25
U-234	Bi-210	1.000E+00	1.245E-17	1.924E-16
U-234	Po-210	1.000E+00	3.915E-19	9.842E-18
U-234	∑DSR(j)		2.653E-08	2.586E-08
U-238	U-238	5.400E-05	2.454E-19	2.348E-19
U-238	U-238	9.999E-01	4.545E-15	4.348E-15
U-238	Th-234+D	9.999E-01	1.096E-03	1.161E-03
U-238	U-234	9.999E-01	3.088E-14	1.009E-13
U-238	Th-230	9.999E-01	4.781E-19	3.787E-18
U-238	Ra-226	9.999E-01	1.371E-20	2.383E-19
U-238	Rn-222+D	9.999E-01	3.902E-17	6.974E-16
U-238	Pb-210	9.999E-01	1.234E-32	4.674E-31
U-238	Bi-210	9.999E-01	4.507E-24	1.780E-22
U-238	Po-210	9.999E-01	1.168E-25	7.815E-24
U-238	∑DSR(j)		1.096E-03	1.161E-03

The DSR includes contributions from associated (half-life ≤ 1 day) daughters.

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 2.500E+01 mrem/yr

Nuclide (i)	t= 0.000E+00	1.000E+00
Bi-210	2.331E+08	2.961E+10
Pb-210	7.107E+06	7.054E+06
Po-210	1.091E+08	8.459E+08
Ra-226	2.017E+02	2.038E+02
Rn-222	7.374E+03	1.855E+10
Th-230	9.236E+05	3.084E+05
Th-234	2.123E+05	7.750E+09
U-234	9.422E+08	9.666E+08
U-238	2.282E+04	2.153E+04

Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 0.000E+00 years

Nuclide (i)	Initial (pCi/g)	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
Bi-210	1.000E+01	0.000E+00	1.072E-07	2.331E+08	1.072E-07	2.331E+08
Pb-210	1.000E+01	0.2600 ± 0.0005	3.611E-06	6.922E+06	3.518E-06	7.107E+06
Po-210	1.000E+01	0.000E+00	2.293E-07	1.091E+08	2.293E-07	1.091E+08
Ra-226	1.000E+01	0.0660 ± 0.0001	1.264E-01	1.979E+02	1.239E-01	2.017E+02
Rn-222	1.000E+01	0.000E+00	3.390E-03	7.374E+03	3.390E-03	7.374E+03
Th-230	1.800E+00	1.000E+00	8.106E-05	3.084E+05	2.707E-05	9.236E+05
Th-234	1.100E+00	0.000E+00	1.178E-04	2.123E+05	1.178E-04	2.123E+05
U-234	1.200E+00	0.000E+00	2.653E-08	9.422E+08	2.653E-08	9.422E+08
U-238	1.100E+00	0.3128 ± 0.0006	1.193E-03	2.096E+04	1.096E-03	2.282E+04

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.010E-06	0.000E+00
Bi-210	Pb-210	1.000E+00	3.315E-05	3.216E-05
Bi-210	Ra-226	1.000E+00	4.032E-07	1.208E-06
Bi-210	Rn-222	1.000E+00	1.256E-08	1.223E-08
Bi-210	Th-230	1.000E+00	1.027E-11	7.354E-11
Bi-210	Th-234	1.000E+00	2.604E-24	4.813E-23
Bi-210	U-234	1.000E+00	1.494E-17	2.309E-16
Bi-210	U-238	9.999E-01	4.957E-24	1.958E-22
Bi-210	∑DOSE(j)		3.458E-05	3.338E-05
Po-210	Bi-210	1.000E+00	6.207E-08	8.442E-09
Po-210	Pb-210	1.000E+00	2.027E-06	3.277E-06
Po-210	Po-210	1.000E+00	2.293E-06	2.955E-07
Po-210	Ra-226	1.000E+00	1.849E-08	8.893E-08
Po-210	Rn-222	1.000E+00	7.560E-10	1.244E-09
Po-210	Th-230	1.000E+00	3.822E-13	4.390E-12
Po-210	Th-234	1.000E+00	7.769E-26	2.397E-24
Po-210	U-234	1.000E+00	4.698E-19	1.181E-17
Po-210	U-238	9.999E-01	1.285E-25	8.596E-24
Po-210	∑DOSE(j)		4.401E-06	3.672E-06
Pb-210	Pb-210	1.000E+00	8.571E-14	8.126E-14
Pb-210	Ra-226	1.000E+00	1.051E-15	3.085E-15
Pb-210	Rn-222	1.000E+00	3.188E-17	3.090E-17
Pb-210	Th-230	1.000E+00	2.717E-20	1.896E-19
Pb-210	Th-234	1.000E+00	0.000E+00	0.000E+00
Pb-210	U-234	1.000E+00	4.011E-26	6.004E-25
Pb-210	U-238	9.999E-01	0.000E+00	0.000E+00
Pb-210	∑DOSE(j)		8.679E-14	8.438E-14
Ra-226	Ra-226	1.000E+00	4.224E-04	4.090E-04
Ra-226	Th-230	1.000E+00	1.656E-08	4.897E-08
Ra-226	Th-234	1.000E+00	6.212E-21	4.936E-20
Ra-226	U-234	1.000E+00	3.284E-14	2.249E-13
Ra-226	U-238	9.999E-01	1.508E-20	2.621E-19
Ra-226	∑DOSE(j)		4.224E-04	4.091E-04
Rn-222	Ra-226	1.000E+00	1.239E+00	1.226E+00
Rn-222	Rn-222	1.000E+00	3.390E-02	0.000E+00
Rn-222	Th-230	1.000E+00	4.844E-05	1.456E-04
Rn-222	Th-234	1.000E+00	1.790E-17	1.455E-16
Rn-222	U-234	1.000E+00	9.492E-11	6.638E-10
Rn-222	U-238	9.999E-01	4.292E-17	7.672E-16
Rn-222	∑DOSE(j)		1.273E+00	1.226E+00
Th-230	Th-230	1.000E+00	2.705E-07	2.705E-07
Th-230	Th-234	1.000E+00	1.640E-19	5.462E-19
Th-230	U-234	1.000E+00	7.998E-13	2.353E-12
Th-230	U-238	9.999E-01	5.260E-19	4.165E-18
Th-230	∑DOSE(j)		2.705E-07	2.705E-07

Individual Nuclide Dose Summed Over All Pathways
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	DOSE(j,t), mrem/yr t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.295E-04	3.549E-09
Th-234	U-238	9.999E-01	1.205E-03	1.277E-03
Th-234	∑DOSE(j)		1.335E-03	1.277E-03
U-234	Th-234	1.000E+00	7.118E-15	7.544E-15
U-234	U-234	1.000E+00	3.175E-08	3.037E-08
U-234	U-238	9.999E-01	3.397E-14	1.110E-13
U-234	∑DOSE(j)		3.175E-08	3.037E-08
U-238	U-238	5.400E-05	2.700E-19	2.583E-19
U-238	U-238	9.999E-01	5.000E-15	4.783E-15
U-238	∑DOSE(j)		5.000E-15	4.783E-15

THF(i) is the thread fraction of the parent nuclide.

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Bi-210	Bi-210	1.000E+00	1.000E+01	1.977E-28
Bi-210	Pb-210	1.000E+00	0.000E+00	7.252E+00
Bi-210	Ra-226	1.000E+00	0.000E+00	1.794E-01
Bi-210	Rn-222	1.000E+00	0.000E+00	2.758E-03
Bi-210	Th-230	1.000E+00	0.000E+00	6.903E-06
Bi-210	Th-234	1.000E+00	0.000E+00	2.518E-18
Bi-210	U-234	1.000E+00	0.000E+00	1.339E-11
Bi-210	U-238	9.999E-01	0.000E+00	5.958E-18
Bi-210	∑S(j):		1.000E+01	7.434E+00
Po-210	Bi-210	1.000E+00	0.000E+00	3.683E-02
Po-210	Pb-210	1.000E+00	0.000E+00	5.717E+00
Po-210	Po-210	1.000E+00	1.000E+01	1.289E+00
Po-210	Ra-226	1.000E+00	0.000E+00	9.171E-02
Po-210	Rn-222	1.000E+00	0.000E+00	2.165E-03
Po-210	Th-230	1.000E+00	0.000E+00	2.674E-06
Po-210	Th-234	1.000E+00	0.000E+00	7.508E-19
Po-210	U-234	1.000E+00	0.000E+00	4.216E-12
Po-210	U-238	9.999E-01	0.000E+00	1.503E-18
Po-210	∑S(j):		1.000E+01	7.137E+00
Pb-210	Pb-210	1.000E+00	1.000E+01	9.481E+00
Pb-210	Ra-226	1.000E+00	0.000E+00	2.383E-01
Pb-210	Rn-222	1.000E+00	0.000E+00	3.605E-03
Pb-210	Th-230	1.000E+00	0.000E+00	9.309E-06
Pb-210	Th-234	1.000E+00	0.000E+00	3.459E-18
Pb-210	U-234	1.000E+00	0.000E+00	1.833E-11
Pb-210	U-238	9.999E-01	0.000E+00	8.314E-18
Pb-210	∑S(j):		1.000E+01	9.723E+00
Ra-226	Ra-226	1.000E+00	1.000E+01	9.684E+00
Ra-226	Th-230	1.000E+00	0.000E+00	7.674E-04
Ra-226	Th-234	1.000E+00	0.000E+00	4.680E-16
Ra-226	U-234	1.000E+00	0.000E+00	2.281E-09
Ra-226	U-238	9.999E-01	0.000E+00	1.505E-15
Ra-226	∑S(j):		1.000E+01	9.685E+00
Rn-222	Ra-226	1.000E+00	0.000E+00	7.842E+00
Rn-222	Rn-222	1.000E+00	1.000E+01	2.999E-35
Rn-222	Th-230	1.000E+00	0.000E+00	6.137E-04
Rn-222	Th-234	1.000E+00	0.000E+00	3.690E-16
Rn-222	U-234	1.000E+00	0.000E+00	1.803E-09
Rn-222	U-238	9.999E-01	0.000E+00	1.172E-15
Rn-222	∑S(j):		1.000E+01	7.843E+00
Th-230	Th-230	1.000E+00	1.800E+00	1.800E+00
Th-230	Th-234	1.000E+00	0.000E+00	2.369E-12
Th-230	U-234	1.000E+00	0.000E+00	1.057E-05
Th-230	U-238	9.999E-01	0.000E+00	1.131E-11
Th-230	∑S(j):		1.800E+00	1.800E+00

Individual Nuclide Soil Concentration
Parent Nuclide and Branch Fraction Indicated

Nuclide (j)	Parent (i)	THF(i)	S(j,t), pCi/g t= 0.000E+00	1.000E+00
Th-234	Th-234	1.000E+00	1.100E+00	3.014E-05
Th-234	U-238	9.999E-01	0.000E+00	1.057E+00
Th-234	∑S(j):		1.100E+00	1.057E+00
U-234	Th-234	1.000E+00	0.000E+00	2.852E-07
U-234	U-234	1.000E+00	1.200E+00	1.148E+00
U-234	U-238	9.999E-01	0.000E+00	2.709E-06
U-234	∑S(j):		1.200E+00	1.148E+00
U-238	U-238	5.400E-05	5.940E-05	5.682E-05
U-238	U-238	9.999E-01	1.100E+00	1.052E+00
U-238	∑S(j):		1.100E+00	1.052E+00

THF(i) is the thread fraction of the parent nuclide.

RESCALC.EXE execution time = 27.94 seconds

APPENDIX D

MicroShield Output

APPENDIX D – MICROSHIELD OUTPUT

The following MicroShield Output files provide detailed documentation of the modelling runs and results shown within the software.

MicroShield Modelling Results

Nearby Resident

MicroShield 8.03
ARCADIS (8.03-0000)

Date	By	Checked

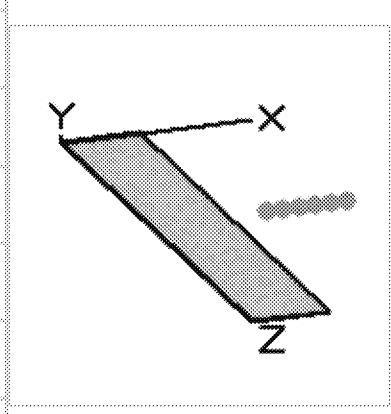
Filename	Run Date	Run Time	Duration
offsite resident no sh dose 125 20 ft step out.msd	October 5, 2019	11:00:28 AM	00:00:12

Project Info	
Case Title	Near Res
Description	Nea Res 10 ft step out
Geometry	13 - Rectangular Volume

Source Dimensions	
Length	1.5e+3 cm (49 ft 2.6 in)
Width	1.0e+4 cm (328 ft 1.0 in)
Height	25.0 cm (9.8 in)

Dose Points

A	X	Y	Z
#1	2.1e+3 cm (69 ft 2.7 in)	125.0 cm (4 ft 1.2 in)	5.0e+3 cm (164 ft 0.5 in)
#2	2.4e+3 cm (79 ft 10.8 in)	125.0 cm (4 ft 1.2 in)	5.0e+3 cm (164 ft 0.5 in)
#3	2.7e+3 cm (89 ft 10.8 in)	125.0 cm (4 ft 1.2 in)	5.0e+3 cm (164 ft 0.5 in)
#4	3.0e+3 cm (99 ft 10.8 in)	125.0 cm (4 ft 1.2 in)	5.0e+3 cm (164 ft 0.5 in)
#5	3.3e+3 cm (109 ft 10.8 in)	125.0 cm (4 ft 1.2 in)	5.0e+3 cm (164 ft 0.5 in)
#6	3.7e+3 cm (119 ft 10.8 in)	125.0 cm (4 ft 1.2 in)	5.0e+3 cm (164 ft 0.5 in)



Shields

Shield N	Dimension	Material	Density
Source	1.32e+04 ft³	Concrete	2.25
Air Gap		Air	0.00122
Immersion		Air	0.00122

Source Input: Grouping Method - Standard Indices
Number of Groups: 25
Lower Energy Cutoff: 0.015
Photons < 0.015: Included
Library: Grove

Nuclide	Ci	Bq	µCi/cm³	Bq/cm³
Bi-210	1.1102e-002	4.1079e+008	2.9606e-005	1.0954e+000
Bi-214	1.0950e-002	4.0516e+008	2.9200e-005	1.0804e+000
Pb-210	1.1102e-002	4.1079e+008	2.9606e-005	1.0954e+000

Pb-214	1.0950e-002	4.0516e+008	2.9200e-005	1.0804e+000
Po-210	1.1105e-002	4.1089e+008	2.9613e-005	1.0957e+000
Po-214	1.0948e-002	4.0507e+008	2.9194e-005	1.0802e+000
Po-218	1.0952e-002	4.0524e+008	2.9206e-005	1.0806e+000
Ra-226	1.0952e-002	4.0523e+008	2.9206e-005	1.0806e+000
Rn-222	1.0952e-002	4.0524e+008	2.9206e-005	1.0806e+000

Buildup: The material reference is Source	
Integration Parameters	
X Direction	20
Y Direction	40
Z Direction	40

Results - Dose Point # 1 - (6.92e+01,4.10e+00,1.64e+02) ft

Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	1.600e+08	1.859e-07	1.963e-07	1.595e-08	1.684e-08
0.05	2.112e+07	4.531e-05	8.584e-05	1.207e-07	2.287e-07
0.08	9.341e+07	6.902e-04	2.207e-03	1.092e-06	3.492e-06
0.1	5.500e+05	6.289e-06	2.295e-05	9.621e-09	3.511e-08
0.2	4.364e+07	1.506e-03	5.649e-03	2.658e-06	9.970e-06
0.3	8.361e+07	5.283e-03	1.775e-02	1.002e-05	3.367e-05
0.4	1.550e+08	1.507e-02	4.597e-02	2.937e-05	8.957e-05
0.5	7.238e+06	9.852e-04	2.783e-03	1.934e-06	5.463e-06
0.6	1.953e+08	3.507e-02	9.276e-02	6.845e-05	1.811e-04
0.8	3.829e+07	1.068e-02	2.565e-02	2.031e-05	4.878e-05
1.0	1.269e+08	4.997e-02	1.120e-01	9.210e-05	2.065e-04
1.5	7.713e+07	5.726e-02	1.144e-01	9.633e-05	1.924e-04
2.0	1.084e+08	1.260e-01	2.356e-01	1.949e-04	3.643e-04
Totals	**1.111e+09**	**3.026e-01**	**6.548e-01**	**5.173e-04**	**1.135e-03**

Results - Dose Point # 2 - (79.9,4.10e+00,1.64e+02) ft

Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	1.600e+08	1.672e-08	1.781e-08	1.434e-09	1.528e-09
0.05	2.112e+07	2.288e-05	4.501e-05	6.094e-08	1.199e-07
0.08	9.341e+07	3.636e-04	1.228e-03	5.754e-07	1.943e-06
0.1	5.500e+05	3.352e-06	1.295e-05	5.128e-09	1.982e-08
0.2	4.364e+07	8.221e-04	3.240e-03	1.451e-06	5.718e-06
0.3	8.361e+07	2.917e-03	1.021e-02	5.533e-06	1.937e-05
0.4	1.550e+08	8.382e-03	2.648e-02	1.633e-05	5.159e-05
0.5	7.238e+06	5.509e-04	1.605e-03	1.081e-06	3.149e-06
0.6	1.953e+08	1.969e-02	5.351e-02	3.843e-05	1.045e-04
0.8	3.829e+07	6.031e-03	1.481e-02	1.147e-05	2.818e-05
1.0	1.269e+08	2.834e-02	6.476e-02	5.225e-05	1.194e-04

1.5	7.713e+07	3.271e-02	6.626e-02	5.503e-05	1.115e-04
2.0	1.084e+08	7.231e-02	1.367e-01	1.118e-04	2.114e-04
Totals	**1.111e+09**	**1.721e-01**	**3.789e-01**	**2.940e-04**	**6.569e-04**

Results - Dose Point # 3 - (89.9,4.10e+00,1.64e+02) ft

Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	1.600e+08	1.970e-09	2.113e-09	1.689e-10	1.813e-10
0.05	2.112e+07	1.384e-05	2.803e-05	3.686e-08	7.468e-08
0.08	9.341e+07	2.280e-04	8.056e-04	3.609e-07	1.275e-06
0.1	5.500e+05	2.124e-06	8.601e-06	3.249e-09	1.316e-08
0.2	4.364e+07	5.315e-04	2.182e-03	9.381e-07	3.852e-06
0.3	8.361e+07	1.904e-03	6.896e-03	3.612e-06	1.308e-05
0.4	1.550e+08	5.506e-03	1.791e-02	1.073e-05	3.489e-05
0.5	7.238e+06	3.635e-04	1.086e-03	7.135e-07	2.131e-06
0.6	1.953e+08	1.304e-02	3.623e-02	2.545e-05	7.071e-05
0.8	3.829e+07	4.014e-03	1.004e-02	7.634e-06	1.909e-05
1.0	1.269e+08	1.893e-02	4.390e-02	3.489e-05	8.093e-05
1.5	7.713e+07	2.196e-02	4.498e-02	3.695e-05	7.568e-05
2.0	1.084e+08	4.871e-02	9.292e-02	7.533e-05	1.437e-04
Totals	**1.111e+09**	**1.152e-01**	**2.570e-01**	**1.966e-04**	**4.454e-04**

Results - Dose Point # 4 - (99.9,4.10e+00,1.64e+02) ft

Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	1.600e+08	2.484e-10	2.686e-10	2.131e-11	2.304e-11
0.05	2.112e+07	9.036e-06	1.881e-05	2.407e-08	5.010e-08
0.08	9.341e+07	1.542e-04	5.668e-04	2.440e-07	8.969e-07
0.1	5.500e+05	1.450e-06	6.126e-06	2.218e-09	9.372e-09
0.2	4.364e+07	3.698e-04	1.577e-03	6.527e-07	2.783e-06
0.3	8.361e+07	1.337e-03	4.994e-03	2.536e-06	9.474e-06
0.4	1.550e+08	3.888e-03	1.298e-02	7.575e-06	2.529e-05
0.5	7.238e+06	2.578e-04	7.874e-04	5.060e-07	1.546e-06
0.6	1.953e+08	9.274e-03	2.628e-02	1.810e-05	5.130e-05
0.8	3.829e+07	2.868e-03	7.287e-03	5.455e-06	1.386e-05
1.0	1.269e+08	1.357e-02	3.189e-02	2.501e-05	5.879e-05
1.5	7.713e+07	1.582e-02	3.272e-02	2.662e-05	5.505e-05
2.0	1.084e+08	3.520e-02	6.765e-02	5.443e-05	1.046e-04
Totals	**1.111e+09**	**8.274e-02**	**1.868e-01**	**1.411e-04**	**3.237e-04**

Results - Dose Point # 5 - (109.9,4.10e+00,1.64e+02) ft

Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	1.600e+08	3.281e-11	3.567e-11	2.814e-12	3.060e-12

0.05	2.112e+07	6.211e-06	1.326e-05	1.655e-08	3.533e-08
0.08	9.341e+07	1.097e-04	4.178e-04	1.735e-07	6.611e-07
0.1	5.500e+05	1.040e-06	4.569e-06	1.591e-09	6.990e-09
0.2	4.364e+07	2.702e-04	1.192e-03	4.768e-07	2.104e-06
0.3	8.361e+07	9.849e-04	3.786e-03	1.868e-06	7.182e-06
0.4	1.550e+08	2.880e-03	9.848e-03	5.612e-06	1.919e-05
0.5	7.238e+06	1.917e-04	5.977e-04	3.763e-07	1.173e-06
0.6	1.953e+08	6.916e-03	1.996e-02	1.350e-05	3.896e-05
0.8	3.829e+07	2.148e-03	5.537e-03	4.085e-06	1.053e-05
1.0	1.269e+08	1.019e-02	2.425e-02	1.878e-05	4.470e-05
1.5	7.713e+07	1.194e-02	2.491e-02	2.008e-05	4.191e-05
2.0	1.084e+08	2.663e-02	5.156e-02	4.118e-05	7.972e-05
Totals	**1.111e+09**	**6.226e-02**	**1.421e-01**	**1.062e-04**	**2.462e-04**

Results - Dose Point # 6 - (119.9,4.10e+00,1.64e+02) ft

Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	1.600e+08	4.477e-12	4.878e-12	3.840e-13	4.184e-13
0.05	2.112e+07	4.431e-06	9.697e-06	1.180e-08	2.583e-08
0.08	9.341e+07	8.090e-05	3.188e-04	1.280e-07	5.045e-07
0.1	5.500e+05	7.741e-07	3.523e-06	1.184e-09	5.390e-09
0.2	4.364e+07	2.045e-04	9.315e-04	3.610e-07	1.644e-06
0.3	8.361e+07	7.515e-04	2.965e-03	1.425e-06	5.624e-06
0.4	1.550e+08	2.209e-03	7.718e-03	4.303e-06	1.504e-05
0.5	7.238e+06	1.475e-04	4.686e-04	2.896e-07	9.199e-07
0.6	1.953e+08	5.337e-03	1.566e-02	1.042e-05	3.056e-05
0.8	3.829e+07	1.664e-03	4.345e-03	3.164e-06	8.265e-06
1.0	1.269e+08	7.914e-03	1.904e-02	1.459e-05	3.510e-05
1.5	7.713e+07	9.310e-03	1.959e-02	1.566e-05	3.296e-05
2.0	1.084e+08	2.082e-02	4.058e-02	3.220e-05	6.276e-05
Totals	**1.111e+09**	**4.844e-02**	**1.116e-01**	**8.255e-05**	**1.934e-04**

MicroShield Modelling Results

Truck Driver

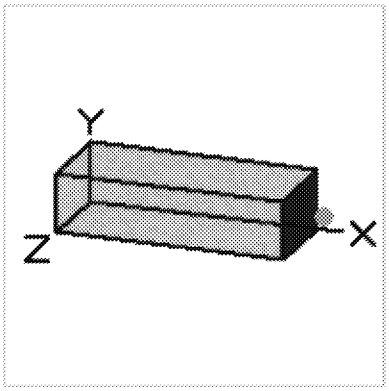
MicroShield 8.03
ARCADIS (8.03-0000)

Date	By	Checked

Filename	Run Date	Run Time	Duration
trucker.msd	June 13, 2019	2:53:24 PM	00:00:02

Project Info	
Case Title	Trucker Shield
Description	Trucker isotopes
Geometry	13 - Rectangular Volume

Source Dimensions	
Length	518.16 cm (17 ft)
Width	213.36 cm (7 ft 0.0 in)
Height	137.16 cm (4 ft 6.0 in)



Dose Points

A	X	Y	Z
#1	579.12 cm (19 ft)	68.58 cm (2 ft 3.0 in)	106.68 cm (3 ft 6.0 in)

Shields

Shield N	Dimension	Material	Density
Source	1.52e+07 cm³	Phosphogypsum	1.12
Shield 1	1.0 cm	Iron	1
Air Gap		Air	0.00122

Source Input: Grouping Method - Standard Indices
Number of Groups: 25
Lower Energy Cutoff: 0.015
Photons < 0.015: Included
Library: Grove

Nuclide	Ci	Bq	µCi/cm³	Bq/cm³
Bi-210	4.6308e-004	1.7134e+007	3.0539e-005	1.1299e+000
Bi-214	4.5673e-004	1.6899e+007	3.0120e-005	1.1144e+000
Pb-210	4.6308e-004	1.7134e+007	3.0539e-005	1.1299e+000
Pb-214	4.5673e-004	1.6899e+007	3.0120e-005	1.1144e+000
Po-210	4.6319e-004	1.7138e+007	3.0546e-005	1.1302e+000
Po-214	4.5664e-004	1.6896e+007	3.0114e-005	1.1142e+000
Po-218	4.5682e-004	1.6902e+007	3.0126e-005	1.1147e+000
Ra-226	4.5682e-004	1.6902e+007	3.0126e-005	1.1147e+000
Rn-222	4.5682e-004	1.6902e+007	3.0126e-005	1.1147e+000

Buildup: The material reference is Source
Integration Parameters

X Direction	30
Y Direction	40

Z Direction	40

Results					
Energy (MeV)	**Activity (Photons/sec)**	**Fluence Rate MeV/cm²/sec No Buildup**	**Fluence Rate MeV/cm²/sec With Buildup**	**Exposure Rate mR/hr No Buildup**	**Exposure Rate mR/hr With Buildup**
0.015	6.674e+06	1.465e-32	1.756e-27	1.256e-33	1.507e-28
0.05	8.807e+05	1.356e-04	6.019e-04	3.612e-07	1.603e-06
0.08	3.896e+06	9.139e-03	4.703e-02	1.446e-05	7.443e-05
0.1	2.294e+04	1.037e-04	5.040e-04	1.587e-07	7.710e-07
0.2	1.820e+06	2.914e-02	1.090e-01	5.143e-05	1.923e-04
0.3	3.487e+06	1.010e-01	3.231e-01	1.917e-04	6.128e-04
0.4	6.467e+06	2.835e-01	8.134e-01	5.523e-04	1.585e-03
0.5	3.019e+05	1.825e-02	4.822e-02	3.582e-05	9.465e-05
0.6	8.148e+06	6.413e-01	1.587e+00	1.252e-03	3.098e-03
0.8	1.597e+06	1.912e-01	4.293e-01	3.638e-04	8.165e-04
1.0	5.291e+06	8.801e-01	1.842e+00	1.622e-03	3.394e-03
1.5	3.217e+06	9.767e-01	1.819e+00	1.643e-03	3.060e-03
2.0	4.522e+06	2.098e+00	3.649e+00	3.244e-03	5.643e-03
Totals	**4.633e+07**	**5.228e+00**	**1.067e+01**	**8.971e-03**	**1.857e-02**

MicroShield Modelling Results

Utility Worker

MicroShield 8.03
ARCADIS (8.03-0000)

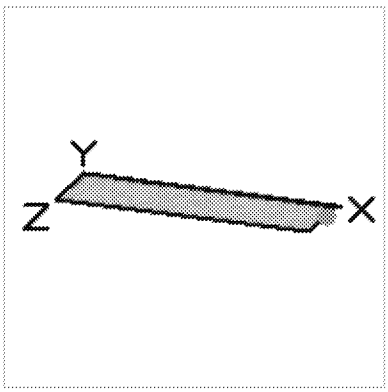
Date	By	Checked

Filename	Run Date	Run Time	Duration
Case2	May 16, 2019	10:26:48 AM	00:00:01

Project Info	
Case Title	Case 2
Description	Case 2
Geometry	13 - Rectangular Volume

Source Dimensions	
Length	5.0e+3 cm (164 ft 0.5 in)
Width	1.5e+3 cm (49 ft 2.6 in)
Height	25.0 cm (9.8 in)

Dose Points			
A	X	Y	Z
#1	5.1e+3 cm (167 ft 3.9 in)	25.0 cm (9.8 in)	750.0 cm (24 ft 7.3 in)



Shields			
Shield N	Dimension	Material	Density
Source	187.5 m³	Concrete	2.25
Air Gap		Air	0.00122

Source Input: Grouping Method - Standard Indices
Number of Groups: 25
Lower Energy Cutoff: 0.015
Photons < 0.015: Included
Library: Grove

Nuclide	Ci	Bq	µCi/cm³	Bq/cm³
Bi-210	5.7634e-003	2.1324e+008	3.0738e-005	1.1373e+000
Bi-214	5.6843e-003	2.1032e+008	3.0316e-005	1.1217e+000
Pb-210	5.7633e-003	2.1324e+008	3.0738e-005	1.1373e+000
Pb-214	5.6843e-003	2.1032e+008	3.0316e-005	1.1217e+000
Po-210	5.7647e-003	2.1329e+008	3.0745e-005	1.1376e+000
Po-214	5.6831e-003	2.1028e+008	3.0310e-005	1.1215e+000
Po-218	5.6855e-003	2.1036e+008	3.0322e-005	1.1219e+000
Ra-226	5.6854e-003	2.1036e+008	3.0322e-005	1.1219e+000
Rn-222	5.6855e-003	2.1036e+008	3.0322e-005	1.1219e+000

Buildup: The material reference is Air Gap
Integration Parameters

X Direction	30
Y Direction	30
Z Direction	20

Results					
Energy (MeV)	**Activity (Photons/sec)**	**Fluence Rate MeV/cm²/sec No Buildup**	**Fluence Rate MeV/cm²/sec With Buildup**	**Exposure Rate mR/hr No Buildup**	**Exposure Rate mR/hr With Buildup**
0.015	8.306e+07	1.233e-65	1.355e-27	1.058e-66	1.162e-28
0.05	1.096e+07	1.523e-06	6.656e-05	4.056e-09	1.773e-07
0.08	4.849e+07	2.526e-04	9.497e-03	3.998e-07	1.503e-05
0.1	2.855e+05	3.355e-06	9.744e-05	5.133e-09	1.491e-07
0.2	2.266e+07	1.330e-03	1.592e-02	2.347e-06	2.810e-05
0.3	4.340e+07	5.516e-03	4.181e-02	1.046e-05	7.932e-05
0.4	8.048e+07	1.737e-02	9.876e-02	3.385e-05	1.924e-04
0.5	3.757e+06	1.215e-03	5.650e-03	2.384e-06	1.109e-05
0.6	1.014e+08	4.537e-02	1.816e-01	8.856e-05	3.544e-04
0.8	1.988e+07	1.474e-02	4.763e-02	2.804e-05	9.059e-05
1.0	6.585e+07	7.183e-02	2.017e-01	1.324e-04	3.718e-04
1.5	4.004e+07	8.670e-02	1.963e-01	1.459e-04	3.303e-04
2.0	5.629e+07	1.949e-01	3.929e-01	3.013e-04	6.076e-04
Totals	**5.765e+08**	**4.392e-01**	**1.192e+00**	**7.456e-04**	**2.081e-03**

ARCADIS Design & Consultancy for natural and built assets

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www.arcadis.com

Administrative Record Index[1]

1.	EPA, Potential Sues and Risks, Background Information Document (1992)
2.	EPRI, Comparison of Coal Combustion Products to Other Common Materials, Chemical Characteristics (2010)
3.	EPRI, Composition and Leaching of FGD Gypsum and Mined Gypsum (2011)
4.	ICRP 2007 report.
5.	EPA Letter to the Florida Institute of Phoshate Research conditionally approving the petition to approve Use of Phosphogypsum as Cover Material in a Landfill Test Cell (December 22, 2004).

[1] All of the documents cited in the Petition are incorporated by reference in the administrative record.

United States
Environmental Protection
Agency

Air And
Radiation
(ANR-459)

402-R92-002
May 1992

EPA

Potential Uses Of Phosphogypsum And Associated Risks

Background Information Document

Printed on Recycled Paper

40 CFR 61 Subpart R
National Emission Standards for
Radon Emissions from
Phosphogypsum Stacks

402-R-92-002

POTENTIAL USES OF PHOSPHOGYPSUM AND ASSOCIATED RISKS

BACKGROUND INFORMATION DOCUMENT

for

40 CFR 61 Subpart R
National Emission Standards for
Radon Emissions from
Phosphogypsum Stacks

Craig Conklin
Work Assignment Manager

Prepared Under
Contract No. 68D90170
Work Assignment No. 1-106

Prepared for
U.S. Environmental Protection Agency
Office of Radiation Programs
401 M Street, S.W.
Washington, D.C. 20460

May 1992

DISCLAIMER

Mention of any specific product or trade name in this report does not imply an endorsement or guarantee on the part of the Environmental Protection Agency

ED_005285_00000283-00005

PREFACE

The Environmental Protection Agency (EPA) is promulgating revisions to 40 CFR Part 61, Subpart R, National Emission Standards for Radon Emissions From Phosphogypsum Stacks. This Background Information Document (BID) has been prepared in support of the rulemaking. This BID contains an introduction, a general description of the fertilizer industry, a discussion of the physical and radiological characteristics of phosphogypsum, a discussion of the uses of phosphogypsum, analyses of the radiological risks associated with various uses of phosphogypsum, and an analysis of the availability and costs of substitute materials.

Copies of this BID, in whole or in part, are available to all interested persons. For additional information, contact Craig Conklin at (703) 308-8755 or write to:

Director, Criteria and Standards Division
Office of Radiation Programs (ANR-46OW)
U.S. Environmental Protection Agency
401 M Street, SW
Washington, D.C. 20460

ED_005285_00000283-00006

LIST OF PREPARERS

Various staff members from EPA's Office of Radiation Programs contributed to the development and preparation of the BID:

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1. INTRODUCTION

1.1 FEDERAL REGULATORY BACKGROUND

The off-site use of phosphogypsum was prohibited by the final National Emission Standards for Hazardous Air Pollutants (NESHAPs) for radionuclides promulgated at 40 CFR Part 61, Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks (54 FR 51654, December 15, 1989). This rule requires that as of the effective date of the rule (March 15, 1990), phosphogypsum be disposed of in stacks or in mines, prohibiting uses of phosphogypsum in construction, agriculture, or research and development.

Because of concerns about the potential impact on farmers, researchers, and other users of phosphogypsum, a Notice of Limited Reconsideration was published in the Federal Register on April 10, 1990 (55 FR 13480). Simultaneously EPA issued a limited class waiver allowing the continued use of phosphogypsum for agricultural application during the 1990 growing season. This waiver had an expiration date of October 1, 1990. However, the waiver was extended on September 28, 1990 with an expiration date of June 1, 1991 (55 FR 40834), and again on May 16, 1991 with an expiration date of October 1, 1991 (56 FR 23519). When the waiver expired on October 1, 1991, all persons holding stacks of phosphogypsum became subject to the work practice requirements in subpart R.

In conjunction with the Notice of Limited Reconsideration, EPA issued a notice of proposed rulemaking at 55 FR 13482 which contains the following options:

1) Retain Subpart R as promulgated on December 15, 1989;

2) Establish a threshold level of radium-226 which would further define the term "phosphogypsum";

3) Allow, upon prior EPA approval, the use of discrete quantities of phosphogypsum for the research and development of processes to remove radium-226 from phosphogypsum, to the extent that such use is at least as protective of public health as is disposal of phosphogypsum in stacks or mines; and/or

4) Allow, upon prior EPA approval, other alternative use(s) of phosphogypsum to the extent that such use(s) is at least as protective of public health as is disposal of phosphogypsum in stacks or mines.

1.2 PURPOSE AND SCOPE OF THE BID

This Background Information Document (BID) provides information relative to the management, disposal and potential uses of phosphogypsum. It also contains an assessment

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of the radiological risks associated with agricultural, construction, and research and development applications of phosphogypsum.

The BID contains a detailed description of the Agency's procedures and methods for estimating the radiological risks associated with the potential uses of phosphogypsum. The material is arranged as shown in the following descriptions of the chapters and appendices.

- Chapter 2 - A general description of the phosphoric acid industry, including phosphate rock, fertilizer, and phosphogypsum production rates and the nature and composition of phosphogypsum.

- Chapter 3 - A description of the potential uses of phosphogypsum, including the quantity of material utilized for each use, and the scope of ongoing research activities.

- Chapter 4 - A detailed description of the risk assessment performed and the results obtained.

- Chapter 5 - A discussion of the availability of nonradioactive materials that could compete with phosphogypsum and the costs associated with their use.

- Chapter 6 - References.

- Appendix A - A description of the PATHRAE pathway equations used in the assessments.

- Appendix B - A description of the Ra-226 soil concentration calculations used in the assessments.

- Appendix C - The risk assessment for the ingestion of soil treated with phosphogypsum based on different application rates and exposure periods.

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2. GENERAL DESCRIPTION OF THE FERTILIZER INDUSTRY

2.1 FERTILIZER PRODUCTION

Modern agricultural practice uses large amounts of chemical fertilizers to replenish and supplement the nutrients that growing plants take up from the soil. A number of chemical elements are required to support vigorous plant growth. Most soils contain adequate trace amounts of the minor chemicals required, but to maintain the long-term fertility of the soil, quantities of nitrogenous material, phosphates, and compounds of potassium and sulfur must be replaced.

Phosphorus fertilizer requirements can be met by the application of chemicals derived from natural deposits of what is known as phosphate rock. Phosphate rock does not have a definite chemical composition, and the composition varies in different mining areas. The major phosphorus materials in the rock are geologically in the apatite group, which in high grade ores is about seventy percent calcium phosphate and is mixed with a large number of impurities, such as calcium fluoride, chlorides, chromium, rare earths, and radionuclides.

Extensive deposits of phosphate rock are found in Florida, Tennessee, and North Carolina. Workable deposits are also found in Idaho. The phosphate rock is recovered by open pit mining. Phosphate rock is transported to a washing plant where it is separated from accompanying soil, stones, etc. Particles less than 200 mesh size are called slimes and are separated from the ore at the washing plant creating a slurry of up to one third the total mined tonnage. The slurry is discharged to slime ponds. The material larger than 200 mesh size is treated in an amine flotation circuit to remove the silica sand from the ore, dried, and ground into particle sizes of 150 micrometers or less. The calcium phosphate is nearly insoluble in water and, to be useful as fertilizer, must be converted into a soluble form. This is most commonly done by converting the phosphate content of the rock into phosphoric acid. There are wet and dry processes for doing the conversion. United States production facilities utilize a wet process where the prepared material is digested with sulfuric acid to produce the phosphoric acid. Phosphoric acid is water soluble and can be concentrated, as desired, by evaporating water from the mixture. The byproduct remaining after the acid conversion is largely calcium sulfate and has been given the name phosphogypsum. Gypsum is the common tradename for calcium sulfate, a common building material.

The phosphogypsum product appears as the dihydrate or the hemihydrate form (water molecules attached to the calcium sulfate molecule), depending on the specific processing details. This byproduct material, filtered from the phosphoric acid, is transferred as a water slurry to open air storage areas known as stacks. A stack can be created by filling a previously mined area or constructed directly on the land surface.

2.1.1 Phosphate Rock

Phosphate rock, mined in open-pit mines, consists of about one-third quartz sand,

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one-third clay minerals, and one-third phosphate particles. After mining, the ore is processed by beneficiation (washing and flotation processes), followed by drying of the marketable rock. The production of phosphate rock in the United States during 1988 was estimated to be 38 million metric tons (MT)[a] (TFI89). Production in the United States peaked in 1980 when 54 million MT were produced (TVA86), and has since declined at a rate of about 3 percent per year (TVA86, TFI89, BOM88). Phosphate rock inventories have also decreased, from 15 to 7.5 million MT in 1985 and 1988, respectively (TFI89).

Phosphate ores mined in the United States contain uranium concentrations ranging from about 7 to 67 pCi/g (20-200 ppm)[b] (SCA91). This is 10 to 100 times higher than the uranium concentration in typical rocks (1 to 2 ppm). Uranium decay products, such as radium-226, exist with the uranium at near secular equilibrium levels. Actual radium-226 concentrations in central Florida phosphate ore range from 18-84 pCi/g, with an average value of 38 pCi/g (Ro87a). Thorium-232 occurs in the ore at much lower concentrations, ranging between 0.1 to 0.6 pCi/g (SCA91).

2.1.2 The Wet Process

In general, the wet process for manufacturing phosphoric acid involves four primary operations: raw material feed preparation, phosphate rock digestion, filtration, and concentration. The phosphate rock is generally dried in direct-fired rotary kilns, ground to a fineness of less than 150 μm for improved reactivity, and digested in a reaction vessel with sulfuric acid to produce the product, phosphoric acid, and the byproduct, phosphogypsum.

Specific wet-acid processes used include the classic Prayon and Nissan-H processes which generate a dihydrate form of phosphogypsum ($CaSO_4 \bullet 2H_2O$), and the Central-Prayon and Nissan-C processes which generate a hemihydrate form of phosphogypsum ($CaSO_4 \bullet \frac{1}{2}H_2O$) (EPA90). The processes that generate the hemihydrate form result in phosphoric acid concentrations of 40 to 50 percent without evaporation, as opposed to the 30 to 35 percent normally produced by the dihydrate processes. It is uncertain which of the above processes are used by each of the phosphoric acid facilities; however, indications are that only two or three facilities use one of the processes which generate the hemihydrate phosphogypsum while the large majority of the facilities use one of the processes which generate the dihydrate phosphogypsum (EPA90). All four processes generate two special wastes: process wastewater and phosphogypsum.

The phosphogypsum is transferred as a slurry to onsite disposal areas referred to as phosphogypsum stacks. These stacks are generally constructed directly on unused or mined-out land with little or no prior preparation of the land surface. The gypsum slurry is pumped

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[a]One metric ton (MT) is approximately 1.1 tons.

[b]1 ppm U-238 = 0.33 pCi/g or 0.67 pCi/g total uranium, U-238 + U-234.

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to the top of the stack where it forms a small impoundment, commonly referred to as a gypsum pond. Gypsum is dredged from the pond on top of the stack and used to increase the height of the dike surrounding the pond. The phosphogypsum stacks become an integral part of the overall wet process. Because the process requires large quantities of water, the water impounded on the stack is used as a reservoir that supplies and balances the water needs of the process. Thus, the stack is not only important as a byproduct storage site, but also contributes to the production process.

As of September 1989, the phosphoric acid production industry consisted of 21 active facilities that use the wet-acid production process (EPA90). Two additional facilities, Agrico's Fort Madison, IA and Hahnville, LA facilities, were on standby at that time. The locations of these facilities are shown in Table 2-1. The majority of the 21 facilities are located in the southeast, with 12 in Florida, three in Louisiana, and one in North Carolina. The combined annual production capacity of 19 reporting facilities is over 11 million MT. In 1988, the aggregate production of nearly 8.5 million MT yielded a capacity utilization rate of about 77 percent (EPA90). Several facilities, however, operated at low utilization rates, e.g., three facilities reported rates of 15.8, 30.1, and 37.5 percent. The generation of 8.5 million MT of P_2O_5[c] would produce an estimated 38 million MT of phosphogypsum, based on 4.5 MT of phosphogypsum per MT P_2O_5 (Gu75).

In 1985, 51 million MT of marketable phosphate rock were produced, of which 41 million MT (80 percent) were used to produce 12 million MT of P_2O_5 by the wet acid process (EPA89a). By 1988, these production figures had dropped to 38 million MT of marketable phosphate rock producing 8.5 million MT of P_2O_5. The main cause for this reduced production, nearly 30 percent, was the poor financial condition of the fertilizer industry during much of the 1980s. These conditions were the result of low domestic demand and reduced foreign purchases (EPA90). About 95 percent of the commercial phosphoric acid produced by the wet process is used in the production of fertilizers and animal feed, with a small portion used as a feedstock in chemical processing operations (BOM87). The data shown in Table 2.2 reflect the use of phosphate fertilizers on major crops, such as coarse grain, wheat, soybeans, and cotton and, as can be seen, the demand for fertilizer closely parallels the acreage of major agricultural crop production. However, the domestic demand for phosphoric acid is expected to increase as a result of the 1988 recovery of the farm economy, and should continue to grow as crop prices and planted acreage increases (EPA90). Non-fertilizer uses of phosphoric acid also declined during the 1980s, due to strict regulations governing the use of phosphates in household products, such as detergents, and a decline in industrial demand (SP88).

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[c]By convention, the phosphate industry relates the production of phosphoric acid to P_2O_5 rather than H_3PO_4.

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Table 2-1. Wet process phosphoric acid plants (EPA90).

Operator	Location	Parent Company
Agrico	Donaldsonville,LA	Freeport-McMoRan
Agrico	Mulberry (Pierce), FL	Freeport-McMoRan
Agrico	Uncle Sam, LA	Freeport-McMoRan
Arcadian	Geismar, LA	Arcadian
Central Phos.	Plant City, FL	CF Industries
CF Chemicals	Bartow (Bonnie), FL	CF Industries
Chevron Chemical	Rock Springs, WY	Chevron Corp.
Conserv	Nichols, FL	Conserv
Farmland, Inc.	Bartow (Pierce), FL	Farmland Ind.
Fort Mead Chemical	Fort Meade, FL	US Agric Chem/WR Grace
Gardinier	Riverview (Tampa), FL	Gardinier
IMC Fertilizer	New Wales (Mulberry), FL	IMC Fertilizer
Mobil Mining	Pasadena, TX	Mobil Corp.
Nu-South Ind.	Pascagoula, MS	Nu-West Industries
Nu-West	Soda Springs, ID	Nu-West Industries
Occidental Chem.	White Springs, FL	Occidental Petroleum
Royster	Mulberry, FL	Cedar Holding Co.
Royster	Palmetto (Piney Pt), FL	Cedar Holding Co.
Seminole Fert.	Bartow, FL	Seminole Fertilizer
J.R. Simplot	Pocatello, ID	J.R. Simplot
Texasgulf	Aurora, NC	Texasgulf
Argico[a]	Ft. Madison, IA	Freeport - McMoRan
Agrico[a]	Hahnville, LA	Freeport - McMoRan

[a] On standby in 1989.

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Table 2-2. Trends in phosphate fertilizer demand and application (BOM88).

-- Year -- Actual/Projected	Fertilizer Demand (million MT)	Major Crop[a] Harvested Areas (million acres)	Application Rates (Kg/acres)
1980	5.5	331	16.6
1981	5.6	351	15.8
1982	5.0	336	15.0
1983	4.4	297	15.0
1984	5.2	324	16.2
1985	4.9	331	15.0
1986	4.5	311	14.2
1987	4.2	289	14.2
1988	4.2	296	14.2
1990	4.4	309	14.2
1995	5.0	333	15.0
Average[b]	4.8	319	15.0

(a) Major crops include coarse grain, wheat, soybeans, and cotton.

(b) Does not include 1990 or 1995 projections.

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2.2 PHOSPHOGYPSUM

2.2.1 Composition of Phosphogypsum

Phosphogypsum, which has an average particle diameter of less than 0.2 mm, is primarily calcium sulfate dihydrate, $CaSO_4 \bullet 2H_2O$, in association with varying amounts of silicon, phosphate and fluoride. Phosphogypsum is only slightly soluble in water, about 2g per liter (EPA89a). Phosphogypsum contains appreciable quantities of radium-226, uranium, and other uranium decay products. This is due to the high uranium concentration in phosphate rock which was discussed in Section 2.1.1. The radionuclides of significance are: uranium-238, uranium-234, thorium-230, radium-226, radon-222, lead-210, and polonium-210. When the phosphate rock is processed through the wet process, there is a selective separation and concentration of radionuclides. Most of the radium-226, about 80 percent, follows the phosphogypsum, while about 86 percent of the uranium and 70 percent of the thorium are found in the phosphoric acid (Gu75).

Table 2-3 shows the average radionuclide concentrations measured in 50 phosphogypsum samples collected in 1985 by EPA from five stacks in central Florida (Ho88). For comparison, the radionuclide concentrations normally observed in uncontaminated rock and soil are also presented. The concentrations measured in the phosphogypsum samples are similar to those previously reported (Gu75) and exceed those in background soil by factors of 10 (uranium) to 60 (radium-226). These radionuclides and radon-222 are possible sources of airborne radioactivity. Radon-222, a decay product of radium-226, is a gaseous element which may diffuse into the air. Also, these radionuclides in particulate form may be resuspended into the air by wind and vehicular traffic. Wind and vehicular traffic are the two principal mechanisms for airborne releases of radioactivity from phosphogypsum stacks.

Table 2-3. Average radionuclide concentrations in phosphogypsum, pCi/g dry weight (Ho88).

Material	Ra-226	U-234	U-238	Th-230	Po-210	Pb-210
Phosphogypsum	31	3.3	3.2	5.1	27	36
Background Soil	0.5	0.3	0.3	0.3	0.5	0.7

The radium-226 concentration in phosphogypsum varies significantly at different sampling locations on a single stack and also in phosphogypsum from different stacks within the same geographical area. This variation is illustrated by the data in Table 2-4. All stacks were active except Estech, which was inactive (closed). The ranges of radium-226 concentrations measured in phosphogypsum collected from stacks in six states are presented

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Table 2-4. Radium-226 concentrations in Florida phosphogypsum samples (Ho88).

Phosphogypsum Stack	Mean Concentration (pCi/g dry)[a]	Concentration Range (pCi/g dry)
Gardinier	33±2	31-37
W.R. Grace	30±9	19-48
Royster	30±11	16-49
Conserv	34±18	23-81
Estech	25±4	19-31

(a). Mean concentration with the standard deviation of samples from 10 locations on each stack.

Table 2-5. Radium-226 concentrations in phosphogypsum, listed by state (EPA90).

State	Phosphogypsum Generated in 1988 (MT)	Ra-226 Concentration in Phosphogypsum (pCi/g)
Florida	29,777,000	5.9-36
Idaho	2,646,000	7.9-23
Louisiana	7,280,000	1.4-26
Mississippi	474,000	5.9-36
North Carolina	5,425,000	4.3-46
Texas	1,157,000	13-15

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in Table 2-5. The radium-226 concentrations observed in phosphogypsum from Louisiana and Mississippi are similar to those observed in Florida, as might be expected since Florida phosphate rock is processed in those states.

The average activity ratios of the major radionuclides in the composite phosphogypsum samples from the central Florida study are shown in Table 2-6. For example, the activity ratio of Ra-226/U-238 is the average radium-226 concentration in phosphogypsum divided by the average uranium-238 concentration in phosphogypsum. These activity ratios indicate that concentrations of uranium and thorium isotopes are depleted in phosphogypsum relative to their concentrations in phosphate rock. However, the concentration of Ra-226 in phosphogypsum is similar to that in phosphate rock. Thus, most of the radium-226 follows the phosphogypsum in the wet process, while most of the uranium and thorium are in the phosphoric acid product.

In addition to radionuclides, phosphogypsum contains some trace metals in concentrations which the EPA believes may pose a potential hazard to human health and the environment (EPA90). Two contaminants, chromium and arsenic, were identified in phosphogypsum from some facilities at concentrations that may pose significant health risks. The concentrations of these contaminants vary greatly in phosphogypsum from different facilities, ranging over three orders of magnitude. Trace metals may also be leached from phosphogypsum, as are radionuclides, and migrate to nearby surface and groundwater resources. The EPA has identified a number of potential constituents in phosphogypsum from some facilities that could, under the appropriate conditions, cause adverse health effects or the restriction of potential uses of nearby surface or groundwater resources. Elements identified include arsenic, lead, cadmium, chromium, fluoride, zinc, antimony, and copper (EPA90). The presence of these trace metals in phosphogypsum is mentioned here in order to provide a more complete description of phosphogypsum, but they will not be addressed in the risk assessment.

2.2.2 Phosphogypsum Stacks

A total of 63 phosphogypsum stacks were identified nationwide in 1989 (EPA89a). Table 2-7 gives the location, size, and status, as of 1989, for each stack. Phosphogypsum stacks were present in 12 different states, with two-thirds located in just four states, Florida, Texas, Illinois and Louisiana. Of the stacks identified, 26 were operating, 24 were inactive, and 13 were considered idle. An operating or active stack is one that is currently receiving gypsum, and an inactive stack is one that is permanently closed. A stack was classified as idle if there were definite plans to reactivate it and it has the characteristics of an active stack, e.g., water may be maintained on the stack top surface and utilized in the water balance for the facility. The phosphogypsum stacks ranged in area from approximately 5 to almost 741 acres, and heights of the stacks ranged from 3 to about 60 meters.

The number of phosphogypsum stacks in each state is given in Table 2-8. The information in this table relates the phosphogypsum stacks to individual states and gives the

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Table 2-6. Average activity ratios of major radionuclides in composite phosphogypsum samples (Ho88).

Radionuclides	Activity Ratio
Ra-226 / U-238	9.1
Th-230 / U-238	1.7
Pb-210 / U-238	13.0
Pb-210 / Ra-226	1.4
Po-210 / Pb-210	0.74
U-234 / U-238	1.1

distribution of stack and stack areas within each category (operating, idle, and inactive). Over half of the operating stacks are in Florida, which accounts for 57 percent of the total base area of all operating stacks. In 1989, the total base area of all phosphogypsum stacks in the United States was approximately 8,490 acres, of which 69 percent was associated with operating stacks, 14 percent with idle stacks, and 17 percent with inactive stacks. From Table 2-8, it is apparent that older inactive stacks are generally much smaller than the newer operating stacks. For example, the average base area of an operating stack was 224 acres, while the average base area of an inactive stack was only 60 acres.

In addition to their large sizes, operating phosphogypsum stacks are characterized by other physical features. Large areas of the stack top are covered by ponds of water, ditches, or beaches (saturated land masses that protrude into the ponds). These surface features may cover up to 75 percent of the top of the stack. Other surface features include areas of loose, dry materials, access roads, and thinly-crusted stack sides. Inactive stacks are characterized by a hard, thick-crusted top and dry, thinly-crusted sides.

2.2.3 Production Rate of Phosphogypsum

The production of phosphogypsum can be estimated by applying the rule of thumb of 4.5 MT of phosphogypsum per Mt of P_2O_5 (Gu75). For illustrative purposes, the annual phosphate rock, phosphoric acid, and phosphogypsum production rates are provided in Table 2-9 for selected years since 1965 (TFI89, TVA86).

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Table 2-7. The location and characteristics of phosphogypsum stacks in the United States (EPA89a).

Facility Name		Location	Stack Status	Stack Height(m)	Base Area(acres)
Districhem Inc.[a]		Helena, AR	Inactive	23[a]	22
Agrico Fertilizer Co.		Bartow, FL	Operating	21	346[a]
Royster Phosphate,Inc[a]		Palmetto, FL	Operating	21	299
Brewster Phosphates		Bradley, FL	Inactive	9	124
CF Industries, Inc.		Plant City, FL	Operating	28	400
CF Industries, Inc.		Bartow, FL	Idle[a]	40	361
Conserv, Inc.	1[b]	Nichols, FL	Operating	10	79
	2		Operating	27	77
Estech, Inc.		Bartow, FL	Inactive	9	27[a]
Farmland Industries,Inc.		Bartow, FL	Operating	20	227
Gardinier, Inc.		Tampa, FL	Operating	54	341
Seminole Fertilizer	1	Bartow, FL	Operating	6	158
Corp.	2		Operating	27	561
IMC Corp.		Mulberry, FL	Operating	24[c]	388[c]
Occidental Chem.Co.	1	White Spgs, FL	Operating	22	99
(Suwanne River)	2		Operating	20	99
Occidental Chemical Co. (Swift Creek)		White Spgs, FL	Operating	18	131
Royster Co.	1	Mulberry, FL	Operating	18	74
	2		Operating	24	44
USS Agri-Chemicals,Inc.		Bartow, FL	Inactive	18	49
USS Agri-Chemicals,Inc.		Ft. Meade, FL	Operating	23	151
Nu-West Ind.,Inc.[a]		Conda, ID	Operating	24	89
J.R. Simplot Co.	1	Pocatello, ID	Idle	12[d]	42[d]
	2		Operating	20[d]	200
Bunker Hill Co. 1		Kellogg, ID	Inactive	8[e]	5[e]
	2		Inactive	8[e]	12[e]
	3		Inactive	8[e]	49[e]
General Chemical Corp.		E.St.Louis, IL	Inactive	9	21

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Table 2-7. The location and characteristics of phosphogypsum stacks in the United States (EPA89a) (continued).

Facility Name		Location	Stack Status	Stack Height(m)	Base Area(acres)
F&W Flying Service, Inc.		Marseilles, IL	Inactive	6	65
Mobil Mining & Minerals Co.		Depue, IL	Inactive	13	135
Northern Petrochem. Co.		Morris, IL	Inactive	4	69
Olin Corp.	1	Joliet, IL	Idle[a]	27	210[a]
	2		Inactive	5	20[a]
Smith Douglas/Borden		Streator, IL	Inactive	18	25[a]
Quantum Chemical Corp.		Tuscola, IL	Inactive	16	79
Agrico Fert. Co.	1	Ft. Madison,IA	Inactive	30	49
	2		Inactive	9	49
	3		Inactive	5	59
Agrico Fertilizer Co.		Donaldsonville, LA	Operating	12	502[f]
Arcadian Corp.	1	Geismar, LA	Idle	20[a]	94[a]
	2		Idle	12[a]	35[a]
	3		Idle	12[a]	27[a]
	4		Operating	6[a]	22[a]
Agrico Fert. Co.[a]		Hahnville, LA	Operating	4	22
Agrico Fert. Co.[a]		Uncle Sam, LA	Operating	20	702[g]
Nu-South Ind., Inc.[a]		Pascagoula, MS	Operating	20	250
Farmers Chemical Co.		Joplin, MO	Inactive	15	69
W.R. Grace and Co.	1	Joplin, MO	Inactive	10[a]	25
	2		Inactive	10[a]	25
Texasgulf Chem. Co.	1	Aurora, NC	Idle[a]	26[a]	40[a]
	2		Idle[a]	18[a]	74[a]
	3		Idle[a]	38[a]	126[a]
	4		Idle[a]	19[a]	126[a]
	5		Operating[a]	20[a]	126[a]
Amoco Oil Co.	1	Texas City, TX	Idle	11	35
	2		Idle	3	5

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Table 2-7. The location and characteristics of phosphogypsum stacks in the United States (EPA89a) (continued).

Facility Name		Location	Stack Status	Stack Height(m)	Base Area(acres)
Kerley Agricultural Chem. of TX Inc.		Pasadena, TX	Inactive	11	27
Mobil Mining and	1	Pasadena, TX	Inactive	27	59
Minerals Div.	2		Inactive[a]	27	89
	3		Operating	30	151
Phillips Chemical Co.		Pasadena, TX	Idle	27	35
Four Court Incorporated		Magna, UT	Inactive[h]	5	299
Chevron Chemical Co.		Rock Sp., WY	Operating	10[i]	450

(a) Jo88b.

(b) Numbers 1,2,3, etc. refer to different stacks at a facility.

(c) Ba88; (d) Si88; (e) Ap88; (f) Wa88b; (g) Wa88a; (h) Co88; (i) Default value.

Note: Information in this table is from PEI85, except for that identified by footnotes (a), and (c) to (i), and relates to 1988-1989 conditions.

These production figures reflect the capacity of the phosphate mining industry for the last 20 years. It is evident from Table 2-9 that the yearly phosphogypsum production has averaged nearly 40 million MT since 1984. However, this estimate may be low, as the estimated quantity of phosphogypsum produced in 1988, 41.9 million MT, is less than the total reported by the EPA for the same year for six of the larger production states, 46.8 million MT (see Table 2-5). The total phosphate waste volume generated in the U.S. from 1910 to 1981 has been estimated at 7.7 billion MT (EPA85). In Central Florida, the phosphoric acid industry produces about 32 million MT of phosphogypsum each year, with a current stockpile of nearly 400 million MT (SCA91).

The amount of phosphogypsum that will be produced in future years is uncertain. Predictions of the amount of phosphogypsum that will be produced during the next 20 years are reported to range from 310 to 910 million MT (SCA91). Thus, although the amount of phosphogypsum that must be managed in future years will certainly be large, it is not possible to predict with a reasonable degree of certainty the growth of the total phosphogypsum inventory in the U.S.

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Table 2-8. Summary of the phosphogypsum stacks in each state-1989 (EPA89a).

State	Number of Stacks	Total Base Areas, acres[a]		
		Operating	Idle	Inactive
Arkansas	1	0	0	22 (1)
Florida	20	3319 (16)	361 (1)	200 (3)
Idaho	6	289 (2)	42 (1)	67 (3)
Illinois	8	0	210 (1)	410 (7)
Iowa	3	0	0	158 (3)
Louisiana	7	1248 (4)	156 (3)	0
Mississippi	1	250 (1)	0	0
Missouri	3	0	0	119 (3)
N. Carolina	5	126 (1)	366 (4)	0
Texas	7	151 (1)	74 (3)	175 (3)
Utah	1	0	0	299 (1)
Wyoming	1	450 (1)	0	0
Total	63	5833 (26)	1209 (13)	1450 (24)
Average Stack Area		224	93	60

[a] Number of stacks is shown in parentheses.

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Table 2-9. Annual phosphate fertilizer production rates.

Year	Phosphate Rock (million MT)	Phosphoric Acid (million MT)	Phosphogypsum (million MT)
1965	26.8	3.5	15.8
1970	35.1	5.2	23.4
1975	44.3	7.0	31.5
1980	54.4	9.8	44.1
1984	49.2	9.9	44.6
1985	44.8	8.9	40.1
1986	32.8	7.4	33.3
1987	35.7	8.1	36.5
1988	38.3	9.3	41.9

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3. USES OF PHOSPHOGYPSUM

3.1 INTRODUCTION

Phosphogypsum is currently being used in several commercial applications with additional research being conducted, primarily by the Florida Institute of Phosphate Research (FIPR), in order to identify new applications and expand existing ones. Currently, applications include (SCA91):

1) fertilizer and conditioner for soils where peanuts and a variety of other crops are grown;

2) backfill and road-base material in roadway and parking lot construction;

3) additive to concrete and concrete blocks;

4) mine reclamation; and

5) recovery of sulfur.

Each application is discussed below. Agriculture, and to a lesser extent mine reclamation, presently utilizes the largest quantities of phosphogypsum. Other uses have not moved past the development stage of field testing in the U.S. However, this could change in the future if present restrictions on the disposal of phosphogypsum are removed. Research is continuing on additional uses of phosphogypsum as a soil conditioner, as well as other uses, e.g., sulfur recovery, in ceramic products, as anti-skid aggregate, and as a concrete aggregate (SCA91).

Due to the absence of low-cost natural gypsum and the lack of long-term storage space, the use of phosphogypsum in Europe and Japan has been much more widespread than in the U.S. These countries have used phosphogypsum extensively in cement, wallboard, and other building materials (SCA91).

Because of the elevated levels of radionuclides, primarily radium-226, in phosphogypsum, building construction materials containing phosphogypsum could result in elevated radiation exposures to building occupants. Phosphogypsum was used by a New Jersey based company in the manufacture of wallboard, partition blocks, and plaster for distribution in the northeastern United States between 1935 and 1946 (Fi78). No wallboard containing phosphogypsum is currently manufactured for commercial use in the United States. Therefore, the use of phosphogypsum in wallboard and the associated risk will not be addressed in this assessment.

Radon measurements conducted in a room constructed of Japanese phosphogypsum wallboard at EPA's National Air and Radiation Environmental Laboratory did not detect any

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increase in indoor radon concentrations (Se88). The emanation fraction was estimated to be less than 2 percent. However, a modular structure constructed of ferrocement panels containing 50 percent phosphogypsum, 25 percent cement, and 25 percent fine aggregate resulted in radon levels, measured under worst-case ventilation conditions (i.e., the structure was made as air-tight as possible) that averaged 4 to 5 pCi/L (Ch87). The upper end of this range is above the level at which the EPA recommends that homeowners take action to determine the long-term average radon concentration in their home (EPA86).

The amount of phosphogypsum currently being used in the U.S. for the above purposes is small compared to the total amount being produced. It has been estimated that only about 5 percent of the U.S. phosphogypsum output is utilized in some way (An88). The quantities of phosphogypsum sold each year are compared in Table 3-1 to the annual production rates at eight facilities (Va89). The phosphogypsum sold at these facilities was primarily for agriculture. Although this survey does not include all facilities, it does indicate the small scale use of phosphogypsum in the United States.

3.2 AGRICULTURAL APPLICATIONS

For more than 30 years, phosphogypsum has been used in the United States as a conditioner for clayey and sodic[a] soils because of its moisture retaining and salt leaching properties. Its use is considered critical to maintaining soil productivity in the southeastern states where highly weathered soils have poor physical properties and high erodability (TFI90a). In addition, phosphogypsum provides needed nutrients, such as calcium and sulfur, to deficient soils. The phosphogypsum in the southeast is used primarily by peanut growers in Georgia, North Carolina, Virginia, and Alabama. Studies have also indicated that phosphogypsum may be beneficial to southeastern soils used to grow tobacco, corn, small grain, and sugar cane. Currently, the state of Georgia is the largest consumer of phosphogypsum, applying 120,000 to 180,000 MT annually to its peanut fields. Application rates vary depending on the crop, soil type, and purpose of the amendment. Phosphogypsum is a source of calcium for peanuts and is added at rates of 0.2-0.4 MT/acre per year. It is applied at higher rates, 0.8-1.2 MT/acre per year, on acidic, crusting soils to improve physical properties and mitigate subsoil acidity (Mi91).

There is also a large demand (estimated 500,000 to 750,000 MT/yr (TFI90a, Va89) for agricultural use of gypsum in California to amend sodic soils growing such crops as citrus, almonds, vegetables, and tomatoes. In 1985, more than 270,000 MT of phosphogypsum were applied to fields in California. The sales of phosphogypsum for agriculture declined sharply to about 84,500 MT in 1988, due primarily to the depletion of phosphogypsum stacks in that state. As a result, phosphogypsum is currently being shipped into California from Utah.

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[a]Soils containing elevated levels of sodium.

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Table 3-1. Quantities of phosphogypsum sold at eight facilities-1988 (Va89).

Facility Name	Location	Tons Sold Per Year	Percent of Annual Facility Production
Arcadian Corp.	Geismer, LA	5,000	0.7
Farmland Industries, Inc.	Bartow, FL	0-5,000	0 - <0.2
Four Court, Inc.	Magna, UT	200,000[a]	[b]
Mobil Mining & Minerals Div.	Pasadena, TX	[c]	10 - 15
Occidental Chemical Co.	White Springs, FL	100,000	<1
Royster Co.	Mulberry, FL	[c]	<1
J.R. Simplot Co.	Pocatello, ID	40,000-50,000	3-4
Texasgulf Chemicals Co.	Aurora, NC	100,000-150,000	2-3

[a] Shipped to San Joaquin Valley, CA.
[b] Facility is inactive, but has about 8 million tons stockpiled.
[c] Information not provided.

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The Fertilizer Institute (TFI) circulated a questionnaire to which eight farmers in California and 30 farmers in Georgia who regularly apply phosphogypsum to their fields responded (TFI90a, Appendix 38). The crops grown in the amended soils in California were almonds and walnuts (69 acres), peaches (40 acres), grapes (20 acres), alfalfa, corn, beans, and oats (1080 acres), and trees (75 acres). The farms in Georgia were used exclusively for growing peanuts, a total of about 4,200 acres. The following results were obtained from this survey.

	Georgia	California
Application, tons/acre	0.06 - 1.0 (0.44)[a]	1.0-2.0 (1.3)
Acres Amended per Farm	5-700 (139)	7-1,000 (183)
Years of Application	3-40 (17.3)	2-15 (10.5)
Average Tillage Depth, inches	1-15 (8.3)	0-18 (7.4)[b]

[a] Average values are given in parenthesis.
[b] Depended significantly on crop.

This is a small sampling of the total farmers that apply phosphogypsum to their fields; however, it probably presents a representative cross-section of this practice, particularly for the peanut farmers in the southeastern United States.

3.3 ROAD CONSTRUCTION

Phosphogypsum, mixed with fly ash, sand, gravel, or cement, has been successfully used in the United States as a base for roads, parking lots, and storage areas. The use of phosphogypsum for road bed construction has been most extensive in the Houston, Texas area (L185, Kr88), with some application in Florida (FIPR88). The quantities of phosphogypsum sold for roadbed construction in Texas and Florida in 1988 was estimated to be about 140,000 MT per year (Kr88). The quantities of phosphogypsum used in North Carolina are not available. However, considering the large amount of phosphogypsum in Florida and the strong demand for aggregate in that state, the use of phosphogypsum in road construction could significantly increase. Some applications of phosphogypsum in roadway and parking lot construction are described below (EPA90, TFI90a).

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1) Phosphogypsum from Mobil's facility in Pasadena, Texas was mixed with fly ash or cement and used as road base on five sections of city streets in La Porte, Texas, near Houston.

2) In Polk County, Florida, 2.4 km of road base was constructed of a compacted mixture of phosphogypsum and granular sand, and surfaced with one to two inches of asphalt.

3) In Columbia County, Florida, a 2-mile stretch of road base was constructed using both 100 percent dihydrated phosphogypsum and mixtures of phosphogypsum and sand in ratios of 1:2, 1:1 and 2:1. The road base was then surfaced with one to two inches of asphalt.

4) Phosphogypsum has been used commercially in North Carolina as a fill and sub-base in roads crossing swampy areas.

5) A mixture of phosphogypsum (13 percent) and concrete was used to pave 1,670 m^2 (2,000 yd^2) of driveways and parking areas at the Florida Institute of Phosphate Research in Bartow, Florida.

Several investigators have studied direct radiation exposures from gamma-rays and radon-222 resulting from the use of phosphogypsum in roadbed construction. Roessler reports external gamma-ray exposures ranging as high as 20 μR/hr over a roadbed constructed on a 100 percent phosphogypsum base, to 10-11 μR/hr over roadways constructed of a 25 percent phosphogypsum/gravel or sand base and paved with asphalt (Ro87b). Radon flux measurements over the roadways generally ranged between 1 to 2 pCi/m^2-s. When the roadbed was sealed with asphalt, the radon flux was less than 1 pCi/m^2-s. Exposures along the sides of the roadways were near the background gamma-ray and flux levels of 8-10 μR/hr and less than 0.1 pCi/m^2-s, respectively. Another source cites similar exposure levels (An88).

3.4 CONCRETE AND CEMENT BLOCKS

Phosphogypsum has been used on a very limited basis in the manufacture of building materials, e.g., concrete and cement blocks. Phosphogypsum is not currently being used in the United States in the manufacture of building materials. It is widely used for this purpose in Europe and Japan. It is believed that the utilization of phosphogypsum as a raw material for building materials will require further evaluation and probably the establishment of standards for final construction materials. The potential demand for phosphogypsum for this purpose is not known, but would probably not be great. An exception may be in Florida where there are large quantities of phosphogypsum and a high demand for cement. Currently, natural gypsum is used extensively in cement; about 19 percent of the natural gypsum used in the United States is used as an additive to cement (EPA90).

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3.5 SULFUR RECOVERY

Extensive research has been conducted to develop a technology to recover sulfur from phosphogypsum. The development stage appears to be complete and the process could become commercially available should the price of sulfur, currently at $110.00/long ton, increase significantly (Ll91). In general, sulfate is converted to sulfur dioxide (SO_2) by a high temperature decomposition of calcium sulfate ($CaSO_4$) in the phosphogypsum. The sulfur dioxide is scrubbed from the gaseous emissions and sent to the facility's chemical plant where it is converted to sulfuric acid (H_2SO_4) which is utilized in the wet-acid process.

A pilot project to produce sulfuric acid and aggregate has operated successfully at the Agrico plant near Uncle Sam, LA (Ll91). Using the circular grate process, the plant utilized about 35 tons of phosphogypsum and other materials to produce about 30 tons of sulfuric acid and 25 tons of aggregate per day. The plant began operation in 1988 but is presently mothballed, a result of the low price of sulfur.

Consolidated Minerals, Inc. proposes to construct on a 17,100 acre site in DeSoto County, Florida, a multi-production facility that will include a sulfur recovery process. The sulfur dioxide recovered will be converted to sulfuric acid and used in the phosphate fertilizer production unit to precipitate calcium sulfate. In addition to the usual phosphate fertilizer products, the process will also produce calcium oxide for use in Portland cement. The waste products from the plant will include a more pure phosphogypsum (dihydrate with some hemihydrate and anhydrate forms) containing lower radium-226 concentrations (reported to be less than 5 pCi/g) and the insoluble impurities that contain most of the radium-226. It is planned to return the latter to the mine site as part of the reclamation process. The plant is presently scheduled to begin operation in late 1994.

3.6 MINE RECLAMATION

An alternative to the disposal of phosphogypsum directly in stacks has been developed in which the phosphogypsum is mixed with a phosphatic clay suspension (a waste from the beneficiation of phosphate rock) in the approximate ratio of 3 parts phosphogypsum to 1 part clay. The suspension is then pumped to the disposal site. The mixture will dewater and become consolidated in about one year, after which the surface can be revegetated with grass and trees.

There are two factors that must be considered in determining if a phosphogypsum facility can utilize this disposal method. First, the facility must be located near the disposal site (mine) to keep transportation costs to a minimum. Second, the phosphatic clay suspension must contain sufficient base (e.g. calcium carbonate) to neutralize the acids remaining in the phosphogypsum.

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Currently, only Texasgulf's facility near Aurora, North Carolina is using this disposal process. At this facility, phosphogypsum is disposed in a mine adjacent to the plant at about the same rate as it is produced (EPA90). Facilities in Florida and Idaho are close enough to mines to make this disposal process feasible. In 1988, mine reclamation could have utilized more than 32 million MT. However, this use is not viable for facilities in Louisiana, Mississippi, and Texas because their phosphate rock is shipped from Florida, nor at the facility in Rock Springs, Wyoming that receives phosphate rock mined in Utah. In 1988, the combined total phosphogypsum generated at these facilities was nearly 10 million MT (EPA90).

Mine reclamation as a means of phosphogypsum disposal is a viable option that may become more prevalent in the future. Two distinct advantages of mine reclamation over the current practice of placing the material in large stacks are the aesthetic advantage of revegetating the mined-out area, and the greatly reduced potential for the waste to be released to surface water by erosion and to the atmosphere by the wind.

3.7 RESEARCH ACTIVITIES

Extensive research is being conducted under the sponsorship of the Florida Institute of Phosphate Research (FIPR) and other organizations to develop commercial uses for phosphogypsum (FIPR87, FIPR89a, FIPR89b, FIPR90a, FIPR90b). Some current and potential uses for phosphogypsum were listed in Section 3.1 and briefly discussed in Sections 3.2 to 3.6. Research and development projects were being actively pursued in all of these applications until the prohibition on its use was enacted on December 15, 1989 (54 FR 51654).

Numerous research efforts have been directed at expanding and developing beneficial uses for phosphogypsum. The major goals of FIPR, an agency of the State of Florida supported financially by the state severance tax on phosphate, are the prevention of further accumulation of phosphogypsum and the reduction of current inventories. FIPR is engaged in research directed toward the recovery of sulfur and other valuable by-products from phosphogypsum; the possible production of building materials such as aggregate, lime, and cement; the use of phosphogypsum as a road-base material; and its use as an agricultural amendment to enhance calcium and sulfur values in the soil.

FIPR and the phosphate industry are not alone in conducting research on possible uses for phosphogypsum. Louisiana State University has established an Institute for Recyclable Materials, one objective of which is the study of beneficial uses of phosphogypsum. Other southeastern universities, including the University of Florida, the University of Miami, and the University of Georgia are also involved in phosphogypsum research.

Research activities related to a few specific potential uses of phosphogypsum are discussed below. This is not intended as a complete listing of current or planned research projects. It is included here only to provide a perspective of the effort being made to

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identify beneficial uses of phosphogypsum and to point out the diversity of the uses being considered.

3.7.1 Agricultural Uses

AGRO Services International, Inc., under a grant sponsored by FIPR, researched the use of phosphogypsum as a fertilizer on several Florida crops (AGRO89). As part of this study, field trials were conducted using various rates and placement of phosphogypsum (holding constant the addition of other fertilizer containing nutrients not found in gypsum) in order to determine the yield response of several crops to phosphogypsum. The study demonstrated that the application of phosphogypsum on crops, other than cowpeas, is very likely to result in strong economic returns.

Other research studies indicate that phosphogypsum can be an important source of calcium and sulfur for soils that are deficient in these elements (FIPR89b, FIPR90a, Da____). In a study of phosphogypsum as a source of sulfur to improve the yield of wheat grown for forage on sandy loams in Florida and Alabama, phosphogypsum was added at annual rates varying between 12 and 121 kg/acre (FIPR90a). Significant increases in yield were observed at an annual application rate of about 40 Kg/acre. Various studies have also indicated the usefulness of phosphogypsum on crops such as tobacco, corn, wheat, and sugar cane grown in Alabama, Louisiana, and North Carolina (Ba80, Go83).

Phosphogypsum has been found useful in controlling soil erosion and maintaining soil productivity on agricultural fields in the southeastern states where highly weathered soils have poor physical properties and are highly erodable (Mi89, Su80, Oa85). Experimental data indicate that phosphogypsum maintains a higher rate of water infiltration for soils compared with mined gypsum. Higher dissolution of the smaller phosphogypsum crystals provides a relatively high electrolyte concentration in the surface soil, sufficient to prevent crust formation. The improvement in water infiltration rates by phosphogypsum application has resulted in significant reductions in surface water runoff which leads to a reduction in soil erosion. Reductions in soil erosion approaching 60 percent have been observed (Wa89).

3.7.2 Construction Materials

Phosphogypsum use in road construction has been tested in the United States. Several research studies have demonstrated that phosphogypsum is suitable for use as a construction aggregate for various applications, including road construction, road embankments, and railroad beds (Ch89, Ch90). Phosphogypsum has been used on an experimental basis for paving and highway construction in both Texas and Florida (see Section 3.3). The addition of gypsum to cement appears to retard the setting times, counteracts shrinkage, increases the strength of the cement product, and provides resistance to sulfate etching.

Phosphogypsum has the same basic properties as natural gypsum and may be used as a substitute for natural gypsum in the manufacture of commercial construction products such

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as plasterboard and plaster of Paris. Phosphogypsum has been used extensively in the manufacture of construction materials in Japan, Australia, and Europe. Currently, however, there are no major uses of phosphogypsum in commercial construction materials in the United States due to the low-cost availability of other suitable materials and to the ban on the utilization of phosphogypsum under 40 CFR Part 61, Subpart R. If the ban on the use of phosphogypsum is lifted, research might well lead to the development of building materials that are suitable for the U.S. market.

3.7.3 Purification of Phosphogypsum

The major disadvantage to the commercial use of phosphogypsum is the presence of potentially hazardous concentrations of radium-226. Research is being conducted in the United States and in other countries to reduce or remove the radium from raw phosphogypsum to ensure its safe use in the agriculture and construction industries. Methods for the removal of radium include hydrocycloning, a physical separation process, and calcining raw phosphogypsum into the hemihydrate form which eliminates most of the radium.

The physical process involves the use of a hydrocyclone to separate the smaller phosphogypsum crystals (less than 30 μm) which contain the greatest portion of the radionuclides from the rest of the phosphogypsum (Pe85). Although this process has proven effective in reducing radium concentrations by factors of 2 to 5, it does not remove all of the radium from the phosphogypsum. A new process, which shows promise of producing phosphogypsum of a much lower radioactive content, involves calcining the raw phosphogypsum into the hemihydrate form ($CaSO_4 \bullet 1/2H_2O$) and dissolving the hemihydrate in water (Mo90). The solution is quickly filtered and the radium salts are collected on the filter media.

Although the hemihydrate process generates a relatively low volume of waste, it is concentrated in radium-226, up to 600 pCi/g, and may pose disposal problems that are equal to or even greater than those associated with the original phosphogypsum (EPA90). No information is available on the volume or radium-226 concentration of the waste resulting from the physical separation method, but it too would probably produce wastes with relatively high concentrations of radium-226. This waste disposal problem will need to be resolved if the purification of phosphogypsum is to become viable.

3.8 SUMMARY OF PHOSPHOGYPSUM UTILIZATION

Probably less than 500,000 MT per year of phosphogypsum are being used in the United States today. The majority is for agricultural applications in California and the peanut producing states in the southeast (approximately 220,000 MT/year). The remaining quantity is for road construction in Texas and Florida (approximately 140,000 MT/yr). Quantities used for mine reclamation are not presently available, but could be substantial in the future if it were decided to dispose of the phosphogypsum by this process. The quantities

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of phosphogypsum used for building materials and research are very small.

The historic usage of phosphogypsum from 1984 through 1987 shows a general decline, primarily due to the closing of the California facilities and the depletion of the phosphogypsum generated in that state. This decline is demonstrated in Table 3-2 (Jo88a, EPA89a).

Table 3-2. Estimated quantities of phosphogypsum used per year (EPA89a).

Year	Total Estimated MT[a]
1984	660,000
1985	460,000
1986	540,000
1987	360,000

[a] These totals are based on the results of a mail survey (Jo88a). Since some of the companies failed to respond to the survey, it does not represent a total response for the industry; however, it is believed that the survey gives an approximate total usage rate.

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4. RADIOLOGICAL ASSESSMENTS OF PHOSPHOGYPSUM USE

4.1 INTRODUCTION

The purpose of this assessment is to analyze the radiological risk associated with various uses of phosphogypsum. The PATHRAE dose assessment model is employed to evaluate potential doses and risks for plausible exposure scenarios involving the commercial use of phosphogypsum. Section 4.3 provides a discussion of the methodology for this risk assessment, including a brief description of the PATHRAE dose assessment model, the exposure scenarios evaluated, and the input parameter values used in the PATHRAE analysis. The results of the risk assessment are summarized in Section 4.4. Risks to workers, to individuals in the critical population group (CPG), and to reclaimers are evaluated for agricultural, road construction, and research and development (R&D) uses of phosphogypsum.

There is some concern that crops grown in soils amended with phosphogypsum may contain elevated concentrations of radionuclides, primarily radium-226, polonium-210, and lead-210 (see Table 2-3). To better understand the significance of this pathway, both long- and short-term uptake studies were conducted at the University of Georgia for the EPA (Mi91). As part of the study, the leachability of radionuclides in amended soils was investigated. The results of the University of Georgia study are presented in Section 4.2.

4.2 RADIOLOGICAL EFFECT OF AMENDING SOILS WITH PHOSPHOGYPSUM

Both long- and short-term studies were conducted by the Agronomy Department at the University of Georgia to determine the significance of the uptake of radionuclides by plants grown in soils treated with phosphogypsum (Mi91). Locations having two different soil types were selected for study: one at Athens, GA where there is a sandy loam topsoil (25-30 cm) overlying a clayey subsoil, and at Tifton, GA where there is a very sandy topsoil (50 cm) over a sandy clay loam subsoil.

4.2.1 Long-Term Study

In 1985, 2 m by 5 m plots were established at both locations and treated with an equivalent of 4 MT/acre (simulating 5 to 10 years of field treatment) of phosphogypsum from Bartow, FL. The phosphogypsum was mixed with the top 15 cm of soil and planted with alfalfa. Similar untreated plots were used as controls. All plots were treated with commercial nitrogen, phosphorus, and potassium fertilizers. Plant tissues were randomly harvested from each plot in 1990, after which five core samples, 5 cm in diameter and 90 cm deep, were obtained from each plot, divided into three sections (0-15 cm, 15-30 cm, and 75-90 cm depths), and combined with respect to the depth increment.

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4.2.2 Short-Term Study

This study was conducted in 1990 at the Athens, GA farm. Plots of 4 m by 5 m were treated with an equivalent of 4 MT/acre of the same phosphogypsum that was used in the long-term study. The phosphogypsum was lightly raked into the soil surface immediately after soybeans had been planted in June. Untreated plots were used as controls. The soybeans were harvested in the fall and separated into leaves (including stems) and seeds.

Prior to analysis, the plant samples were dried at 60°C and ground in a Wiley mill. The soil samples were air-dried and sieved to <2 mm. All samples, including samples of the phosphogypsum used in the studies, were analyzed for isotopic uranium and thorium, radium-226, lead-210, and polonium-210.

Of the pertinent radionuclides, only Ra-226 was consistently present above the detection limit in the soil samples; however, concentrations in samples from the treated plots were no higher than those from the control plots, about 2 pCi/g. The analysis of core samples from fields treated five years earlier with phosphogypsum showed no detectable elevated levels of radionuclides at any depth. These results were attributed to the small quantities of radionuclides added in the phosphogypsum relative to the amounts naturally present in the soil.

Radium-226 was the only radionuclide associated with phosphogypsum that was detected in either alfalfa or soybeans. There were no statistical differences in the concentration of Ra-226 measured in plant tissues grown in the treated and control plots. Although the uptake of Ra-226 was measurably higher in alfalfa grown in Tifton soil than in alfalfa grown in Athens soil (2 pCi/g dry weight vs less than 1 pCi/g dry weight), it was not statistically significantly greater in plants from treated soils than in the controls at the two sites. The dominant radionuclide was potassium-40 in both plant types, ranging from about 7 to 20 pCi/g dry weight.

4.2.3 Leaching Studies

A series of leaching studies was performed as part of the uptake studies (Mi91). Intact soil columns, 10 cm diameter and 30 cm deep, were taken of both Tifton and Athens soils using a truck-mounted hydraulic ram. Two columns of each soil type were treated with an equivalent of 4 MT/acre of the phosphogypsum used in the uptake studies. The phosphogypsum was applied as a powder to the soil surface. Two columns of each soil type were untreated and used as controls. Deionized water was ponded on the surface at a constant 2-cm depth and allowed to perculate through the column until a total of 8 liters of leachate in 1-liter increments had been collected from the column base. This is equivalent to about one year of precipitation.

The leachate was filtered to remove suspended clay particles prior to analysis. The columns were cut into 5-cm sections, and the soil in each section analyzed separately for the

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same radionuclides as listed above for the soil samples.

Only Ra-226 was consistently detected in the leachate of the soil columns. The amount of Ra-226 leached from the treated and untreated Athens soil columns was about the same, totaling 2.2 pCi in the 8 liters collected. However, the Ra-226 concentrations in the leachate of Tifton soil treated with phosphogypsum was 3 to 5 times higher than in the control leachate. The Ra-226 concentration in the leachate peaked at 3 liters (0.8 pCi/L), and then decreased to near the control level after 8 liters were collected. The total amount of Ra-226 collected in the Tifton soil leachate was 6.5 pCi, equivalent to about 5 percent of the Ra-226 initially added in the phosphogypsum. The higher leachability of Ra-226 in the Tifton soil was attributed to the sandy nature of the soil allowing rapid percolation of water with limited adsorption capacity of the soil. No discernable trend was observed in the Ra-226 concentration with soil depth.

Considering the relative immobility of the principal radionuclides associated with phosphogypsum in soil and the small quantities added in the phosphogypsum relative to the amounts naturally present in the soil, 0.7 pCi/g and 1.9 pCi/g of radium-226 in Tifton and Athens soils, respectively, University of Georgia investigators concluded that short-term treatments (5-10 years) of farm lands with phosphogypsum does not pose an acute environmental hazard.

Studies conducted earlier to characterize the radiological hazards associated with soils amended with phosphogypsum produced similar results and conclusions. A University of Florida study of radionuclide uptake by foods grown in soil receiving one ton of phosphogypsum per acre every four years concluded that there would be no significant radiation problems for up to at least 50 years (Ro88). Another study measured the radon flux on three fields that had been amended with varying amounts of phosphogypsum for different periods of time (Po90). The mean of 13 flux measurements, using charcoal canisters, made on each field ranged from 0.4 to 1 pCi/m^2-s. The background flux, measured on areas receiving no application, was 0.4 pCi/m^2-s. It was difficult to correlate the radon flux measurements with the amount of phosphogypsum applied.

4.3 RISK ASSESSMENT METHODOLOGY

The methodology employed in evaluating individual and population risks from commercial uses of phosphogypsum is described in this section. Dose calculations were performed using the PATHRAE dose assessment model (EPA87). Calculations were performed for exposure scenarios which included the use of phosphogypsum in agriculture, road construction, and R&D activities. Where PATHRAE does not model the exposure scenario (e.g., a person performing experimental analyses on phosphogypsum contained in metal drums), the MICROSHIELD computer code (GRO85) was used to augment the results of the PATHRAE analyses. Lifetime risks from one year of exposure were obtained from the PATHRAE dose assessment results using the risk conversion factors in the EPA's Environmental Impact Statement for NESHAPS radionuclides (EPA89b).

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4.3.1 The PATHRAE Dose Assessment Model

The PATHRAE performance assessment model (EPA87) was initially developed as an analytical tool to assist EPA in developing standards for low-level radioactive waste and below regulatory concern waste disposal. The PATHRAE model estimates health effects which could potentially occur if radioactive wastes were disposed of in a near surface facility, sanitary landfill, or other geological setting. PATHRAE can be used to calculate effective dose equivalents[a] to members of a critical population group from the disposal of radioactive material at sites located in diverse hydrogeologic, climatic, and demographic settings. An important PATHRAE model feature is its simplicity in analyzing a comprehensive set of radionuclides, disposal settings, and exposure pathways. The effects of changes in disposal site and facility characteristics can be readily investigated with relatively few parameters needed to define the problem.

PATHRAE models both off-site and on-site pathways through which persons may come in contact with radioactivity from disposed material. The off-site pathways include groundwater transport to a well and a river, surface water runoff to a river, and atmospheric transport of radioactive particulates. On-site pathways include direct gamma exposure, dust inhalation, exposure from foodstuffs grown on-site, and inhalation of radon gas and radon daughters. See Appendix A for a detailed description of the PATHRAE pathway equations.

For this risk assessment, the phosphogypsum is assumed to be mixed with soil in an agricultural field or mixed with other construction materials to construct roadbeds and concrete highways. Exposure scenarios and values for some important input parameters used in modeling these scenarios are described later in this section.

4.3.2 The MICROSHIELD Computer Code

Where the exposure geometry is not readily modeled by PATHRAE (e.g., person exposed to the radioactivity in phosphogypsum contained in metal drums), MICROSHIELD was used to estimate the external gamma dose. MICROSHIELD (GRO85) is a microcomputer adaptation of the ISOSHLD II (Eng66) mainframe code for analyzing gamma radiation shielding. MICROSHIELD has solution algorithms for 14 different geometries which include point, line, sphere, disk, cylinder, plane, and rectangular volume sources; and slab, cylindrical, and spherical shield configurations. MICROSHIELD sorts individual gamma energies from each isotope in the source term into 21 energy groups. Dose rate calculations are performed by one of three geometry-based calculational routines which include analytical expressions, Simpson's rule integration, and point-kernel integration. Execution of the program proceeds by repeating the solution algorithm for each energy group that has any activity until all 21 energy groups have been evaluated.

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[a] Throughout this report the term "dose" refers to the effective whole body dose equivalent.

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The MICROSHIELD code user supplies input information describing the characteristics of the exposure scenario to be evaluated. This input information includes: distance between the source and the exposed individual; source inventory; dimensions of the source region; the dimensions, locations, and orientations of intervening shields; and the material (including air) used for these intervening shields.

4.3.3 Exposure Scenarios

The exposure scenarios evaluated for this phosphogypsum risk assessment include potential exposures to individuals from the use of phosphogypsum in agriculture, road construction, and R&D activities.

4.3.3.1 Phosphogypsum in Agriculture

Seven scenarios involving the agricultural use of phosphogypsum are evaluated. Scenarios 1, 3, and 5 assume a clay soil base type, with the exposed individual being greater than 100 m from the site edge. Scenarios 2, 4, and 6 consider similar pathways, using a sand soil base type, and exposed individuals 100 m from the site boundary. Scenarios 1 through 4 involve the use of phosphogypsum as a source of calcium and sulfur for soils deficient in these elements. Scenarios 5 and 6 involve its use in sediment control for soils that have been eroded and leached. Scenario 7 evaluates the effect of using phosphogypsum containing a range of Ra-226 concentrations with different application rates.

Scenarios 1 through 4: Phosphogypsum as a source of calcium and sulfur for soils deficient in these elements. Parameters which characterize the four scenarios involving phosphogypsum as a source of calcium and sulfur on agricultural fields are shown in Table 4-1. Four scenarios are evaluated: two involving an average phosphogypsum application rate on a moderate size clay or sand field, and another for a maximum application rate on a large clay or sand field. The parameter values in Table 4-1 are based on responses by agricultural users of phosphogypsum to a survey by The Fertilizer Institute (TFI). The reference agricultural fields for Scenarios 1 through 4 are postulated to be located in the southeastern United States. Values of environmental and climatological parameters used in the risk assessment are representative of a humid permeable site.

The dose calculations for Scenarios 1 through 4 assume biennial applications of phosphogypsum to the reference site for a period of 100 years. Phosphogypsum is spread over a field and diluted by mixing with the soil. Hence the incremental radionuclide concentrations in the soil are much lower than the concentrations in the phosphogypsum itself. Over time, as phosphogypsum continues to be applied, the radionuclide concentrations in the soil are expected to increase until equilibrium is reached with competing mechanisms that remove the gypsum, and its radioactive constituents, from the soil. These removal mechanisms include plant uptake, leaching by infiltration of surface water, and wind and water erosion. The radionuclide content in the soil is also reduced as a result of radioactive decay. A simple mass balance equation is used to estimate radionuclide concentrations in the

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Table 4-1. Phosphogypsum use parameters for Scenarios 1 through 4.

	Average Site (Scenario 1&2)	Maximum Site (Scenario 3&4)
Kilograms of phosphogypsum per acre	664	2,032
Acres per farm	138	1,000
Tillage depth (cm)	22	46
Application rate	Biennially	Biennially
Distance to nearest residence (m)	890 & 100	6,440 & 100
Soil Type	Clay, Sand	Clay, Sand

reference soil as a result of biennial applications of phosphogypsum for a period of 100 years. For a Ra-226 concentration of 30 pCi/g in phosphogypsum, the increase in the Ra-226 concentration in the soil after 100 years of biennial application is calculated to be 0.69 pCi/g for Scenarios 1 and 2 and 1.02 pCi/g for Scenarios 3 and 4. A detailed description of the Ra-226 soil concentration calculation method is presented in Appendix B.

Scenarios 5 and 6: Phosphogypsum as sediment control for soils that have been eroded and leached. Parameters which characterize Scenarios 5 and 6 are shown in Table 4-2. The reference agricultural site for this scenario is assumed to be located in south-central California. The phosphogypsum is initially applied at the rate of 8 MT per acre, followed by biennial applications of 4 MT per acre. As in Scenarios 1 through 4, an application period of 100 years is postulated. For a Ra-226 concentration of 30 pCi/g in phosphogypsum, the increase in the Ra-226 concentration in the soil after 100 years of biennial application is calculated to be 3.12 pCi/g for Scenarios 5 and 6.

For Scenarios 1 through 6 the following exposure pathways are evaluated:

- Agricultural Worker
  - Direct gamma exposure
  - Dust inhalation

- On-site Individual
  - Direct gamma exposure
  - Indoor radon inhalation
  - Use of contaminated well water

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- Member of CPG
  - Inhalation of contaminated dust
  - Ingestion of drinking water from a contaminated well
  - Ingestion of foodstuffs contaminated by well water
  - Ingestion of foodstuffs grown on fertilized soil

- Off-Site Individual
  - Ingestion of river water contaminated via the groundwater pathway
  - Ingestion of river water contaminated by surface runoff.

Table 4-2. Phosphogypsum use parameters for Scenarios 5 and 6.

Kilograms of phosphogypsum per acre	
- Initial application	8,000
- Subsequent applications	4,000
Acres per farm	556
Tillage depth (cm)	30
Application rate	biennially
Distance to nearest residence (m)	1,000 & 100
Soil Type	Clay, Sand

The agricultural worker is assumed to spend 2,000 hours per year at the agricultural site, performing activities such as plowing, fertilizing, harvesting, etc. The worker would probably use machinery for most of these activities which would provide some shielding from direct gamma radiation (as in the construction scenarios plowing equipment on average provide a shielding factor of 0.6). However, to ensure conservatism in the results of this risk analysis, no credit for shielding is taken in calculating the dose from direct exposure to gamma radiation.

The on-site individual is assumed to live in a house in a development constructed on a site which was previously used for agriculture. For conservatism, this individual is also assumed to work at this same site.

The CPG is defined to include individuals who might be exposed to the highest doses as a result of normal daily activities. For this phosphogypsum risk assessment, the member of the CPG is assumed to be an adult at the nearest residence as defined in Tables 4-1 and 4-2. The person obtains all water from a well adjacent to the house. Fifty percent of foodstuffs are assumed to be grown on-site.

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Scenario 7: Use of phosphogypsum as a soil amendment based on the application rate and Ra-226 concentration. The purpose of this scenario is to determine if the phosphogypsum containing various concentrations of Ra-226 can be applied for agricultural purposes based on various application rates. To evaluate the feasibility of this approach, risk estimates are performed for the two limiting exposure pathways identified from Scenarios 1-6, direct gamma and indoor radon exposures to the on-site individual. The risks for these exposure pathways are estimated using the following combinations of phosphogypsum application rates and Ra-226 concentrations:

Application Rate (lbs/acre)	Ra-226 Concentration (pCi/g)
500	3, 7, 15, 20, 30, 45, 60
1,000	3, 7, 15, 20, 30, 45
1,500	3, 7, 15, 20, 30
2,500	3, 7, 15, 20
5,000	3, 7, 15
10,000	3, 7, 15

A nine-inch tillage depth is assumed. All other parameters remain constant and are those given above for the average site in the southeastern United States.

4.3.3.2 Phosphogypsum in Road Construction

Four scenarios involving phosphogypsum in road construction are evaluated. Scenarios 8 and 9 involve the use of phosphogypsum in a road base for a secondary road. Scenarios 10 and 11 involve phosphogypsum as an additive to increase the strength of a concrete road surface. These scenarios are shown schematically in Figure 4-1.

Scenarios 8 and 9: Phosphogypsum in a road base for a secondary road. The road base consists of a 1:2 phosphogypsum:soil mixture with a density of 2.25 g/cm^3 (2.25 MT/m^3). Assuming a Ra-226 concentration of 30 pCi/g in phosphogypsum, the Ra-226 concentration in the road base is 10 pCi/g. The road base is 9.15 m (30 ft) wide and 0.25 m (10 inches) thick and is covered by a 0.12 m (5 inch) thickness of asphalt.

Scenarios 10 and 11: Phosphogypsum in a concrete road surface. The concrete road surface incorporates 15 weight percent phosphogypsum. Assuming a Ra-226 concentration of 30 pCi/g in phosphogypsum, the Ra-226 concentration in the road surface is 4.5 pCi/g. The road surface is 7.32 m (24 ft) wide and 0.12 m (5 inches) thick. The road base under the concrete surface is the same as for Scenarios 8 and 9.

For Scenarios 8 through 11 the following exposure pathways are evaluated:

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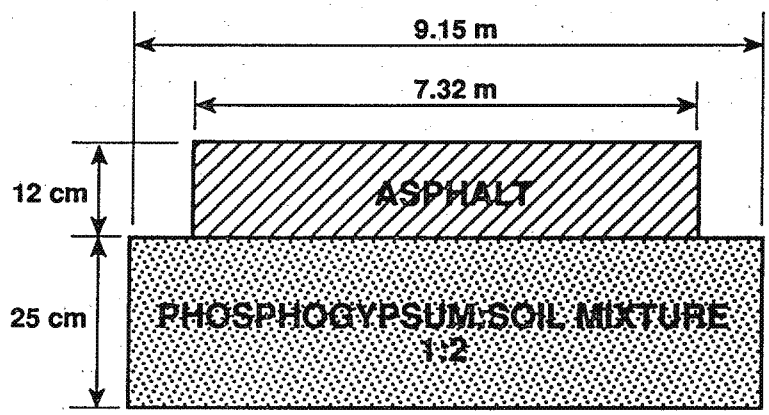
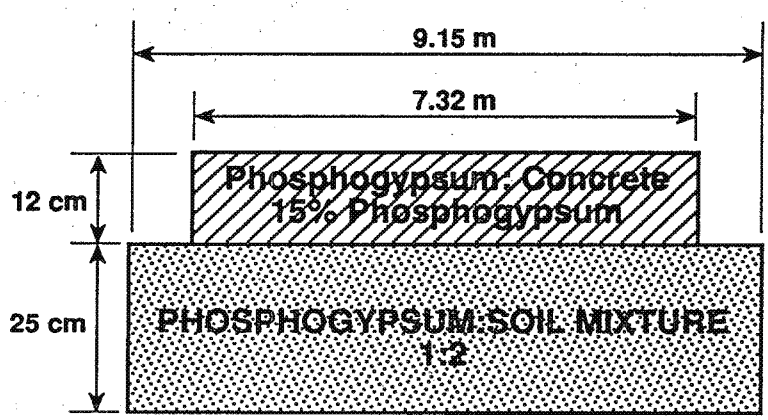


SCENARIOS 8 AND 9
USE OF PHOSPHOGYPSUM IN A ROAD BASE



SCENARIOS 10 AND 11
USE OF PHOSPHOGYPSUM IN A
CONCRETE ROAD SURFACE

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Figure 4-1. Scenarios involving the use of phosphogypsum in road construction.

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- Construction Worker
  - Direct gamma exposure
  - Dust inhalation

- Person Driving on Road
  - Direct gamma exposure

- Member of CPG
  - Direct gamma exposure
  - Ingestion of drinking water from a contaminated well
  - Ingestion of foodstuffs contaminated by well water

- Reclaimer
  - Direct gamma exposure
  - Indoor radon inhalation
  - Use of contaminated well water
  - Ingestion of foodstuffs grown on-site

- Off-Site Individual
  - Ingestion of river water contaminated via the groundwater pathway
  - Ingestion of river water contaminated by surface runoff.

The construction worker is assumed to be engaged eight hours per day for 250 days per year in constructing a 16-km (10-mile) section of road. Gamma exposures are calculated for a worker who is employed directly on the road surface and a worker who uses equipment such as a bulldozer or road grader which provides some shielding from gamma radiation. The shielding coefficient is 0.6.

The person driving on the road is assumed to use the road from home to work, and return. This person travels the road one hour per day for 250 trips per year. The automobile in which this person rides provides some shielding from direct gamma radiation. The shielding coefficient is 0.6.

The reclaimer is assumed to build a house on the roadbed at some future time after the road is closed and the road surface has crumbled and been removed. In addition to living in a house at the site, the reclaimer drills a well for water and plants a vegetable garden in the contaminated soil. The vegetable garden provides 50 percent of the reclaimer's foodstuffs.

The member of the CPG is assumed to live in a house located 100 or 1,000 meters from the road. Potential doses to a member of the CPG could result from direct gamma exposure or from the use of contaminated well water.

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4.3.3.3 Phosphogypsum in Research & Development Activities

One scenario (Scenario 12) is evaluated in which phosphogypsum is used in research and development to evaluate the properties of this material for commercial applications. In this scenario, exposures are estimated for a worker who spends four hours per day, 250 days per year in a laboratory containing one open 55-gallon drum of phosphogypsum. The worker is exposed via direct gamma radiation, dust inhalation, and radon inhalation pathways. MICROSHIELD is used to estimate the external gamma dose; the worker is assumed to be positioned at an average distance of one meter from the drum of phosphogypsum. To estimate the exposure from dust inhalation, a dust loading of 100 micrograms/m^3 is postulated. This value is derived from 40 CFR 50.6(b), which specifies a level of 50 $\mu g/m^3$ as the arithmetic mean level of primary and secondary standards for airborne particulate matter. The value is doubled to provide a conservative estimate. To estimate the indoor radon exposure, two air changes per hour are assumed.

4.3.4 Input Parameters

Values of input parameters used in PATHRAE to evaluate potential doses to individuals and the attendant risks from the commercial use of phosphogypsum are presented in this section. These input parameters include radionuclide concentrations, dose and risk conversion factors, and parameters used to characterize the exposure scenarios described in Section 4.3.3.

4.3.4.1 Radionuclide Concentrations

The relative radionuclide concentrations in phosphogypsum providing the basis for the risk assessment are shown in Table 4-3. The concentrations in Table 4-3 are based on a radium-226 concentration of 1 pCi/g. The risk estimates presented in Section 4 are given as a function of Ra-226 concentration.

The relative concentrations of Pb-210, Po-210, Th-230, U-234, and U-238 are based on average activity ratios of these radionuclides to Ra-226 in phosphogypsum reported in Ho88. The relative concentration of Ra-228 is derived from the activity ratio of Ra-228 to Ra-226 in phosphate fertilizer, reported in SCA91. Activity ratios for Th-228 and Th-232 relative to Ra-226 are also those for phosphate fertilizer, reported in SCA91. Because concentrations of thorium in phosphogypsum are depleted relative to concentrations in phosphoric acid, the use of thorium to radium-226 activity ratios for phosphate fertilizer may tend to overestimate these thorium concentrations. The activity of U-235 in phosphogypsum is assumed to be about 5 percent of the U-238 activity.

4.3.4.2 Dose and Risk Conversion Factors

The dose and risk conversion factors used in this analysis are shown in Table 4-4. Dose conversion factors for ingestion and inhalation are from the EPA's Federal Guidance

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Table 4-3. Phosphogypsum reference radionuclide concentrations.[a]

Radionuclide	Concentration (pCi/g)
Ra-226	1.000
Po-210	1.040
Pb-210	1.400
Th-228	0.133
Ra-228	0.133
Th-230	0.187
Th-232	0.123
U-234	0.120
U-235	0.005
U-238	0.110

[a] Based on a Ra-226 concentration of 1 pCi/g. See text for explanation of activity ratios of other radionuclides relative to Ra-226.

Report No. 11, which provides guidance for control of occupational exposures to radiation (EPA88).

Dose conversion factors for inhalation, ingestion and direct exposure to gamma radiation are from guidance for modifying PRESTO-EPA-CPG to reflect major recent changes in EPA's dose calculation methodology. The inhalation and ingestion conversion factors represent the effective whole body dose equivalents resulting from a unit curie of intake, and the conversion factors for the direct gamma represent the effective whole body dose rates resulting from the exposure to a unit concentration of a curie per square meter on the ground surface. Risk conversion factors in Table 4-4, except those for radon, are based on the radiation risk factors in Table 6-27 of Volume I of EPA's "Environmental Impact Statement for NESHAPS Radionuclides" (EPA89b). As a result of a recommendation by EPA's Science Advisory Board, EPA reduced the radon risk conversion factors by about 37 percent to 4.4×10^{-8} and 4.4×10^{-9} for indoor and outdoor exposures, respectively (Co92). The risk conversion factors represent average lifetime (i.e., 70-year) risks of fatal cancer per unit

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Table 4-4. Dose and risk conversion factors.

I. DOSE CONVERSION FACTORS

Nuclide	Inhalation DCF (mrem/pCi)[a]	Ingestion DCF (mrem/pCi)[a]	Direct Gamma DCF (mrem/yr per pCi/m^2)
Ra-226	8.6E-03	1.3E-03	1.67E-04
Po-210	9.4E-03	1.9E-03	8.55E-10
Pb-210	1.4E-02	5.4E-03	0
Th-228	3.4E-01	4.0E-04	3.37E-04
Ra-228	4.8E-03	1.4E-03	9.04E-05
Th-230	3.3E-01	5.5E-04	8.88E-08
Th-232	1.6E+00	2.7E-03	6.56E-08
U-234	1.3E-01	2.8E-04	8.00E-08
U-235	1.2E-01	2.5E-04	6.41E-08
U-238	1.2E-01	2.7E-04	1.67E-05

(a) 50-year committed dose equivalent from one year of intake (uptake).

II. RISK CONVERSION FACTORS[b]

Nuclide	Inhalation Risk per pCi Inhaled	Ingestion Risk per pCi Ingested	Direct Gamma Risk per pCi/m^2
Ra-226	2.8E-09	9.4E-11	5.7E-11
Po-210	2.4E-09	1.4E-10	2.9E-16
Pb-210	1.4E-09	5.5E-10	0
Th-228	7.2E-08	1.3E-11	4.8E-11
Ra-228	5.8E-10	7.0E-11	3.1E-11
Th-230	2.9E-08	2.3E-11	2.7E-14
Th-232	2.9E-08	2.1E-11	2.0E-14
U-234	2.5E-08	7.5E-11	2.4E-14
U-235	2.3E-08	7.3E-11	5.5E-12
U-238	2.2E-08	7.4E-11	7.23E-13

(b) 70-year lifetime risk of fatal cancer from one year of exposure.

III. RADON RISK CONVERSION FACTORS[c]

Exposure Scenario	Inhalation Risk per pCi/m^3
Indoor Exposure	4.4E-08
Outdoor Exposure	4.4E-09

(c) 70-year lifetime risk of fatal cancer from one year of exposure to Rn-220 and Rn-222 daughters.

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of intake or exposure. A quality factor of 1 has been used to convert from rads to rems for low-LET (i.e., gamma) radiation, and a relative biological effectiveness of 8 has been used to convert from rads to rems for the induction of cancer by high-LET (i.e., alpha) radiation.

4.3.4.3 Site-Specific Input Parameters

Values of all important site-specific input parameters used by PATHRAE in the risk assessments are shown in Table 4-5.

4.4 RESULTS

The results of the phosphogypsum risk assessment are given in this section. Results are presented for the commercial use of phosphogypsum in agriculture, road construction, and research and development. Exposure scenarios used for this risk assessment are described in Section 4.3.

4.4.1 Phosphogypsum in Agriculture

The results of the risk assessment for the use of phosphogypsum in agriculture are summarized in Tables 4-6 through 4-14. Estimated doses and risks for Scenarios 1 and 2, involving an average phosphogypsum application rate on a moderate size clay or sand field used to grow peanuts, are shown in Tables 4-6 and 4-7. Estimated doses and risks for Scenarios 3 and 4, involving a maximum phosphogypsum application rate on a large clay or sand field, are shown in Tables 4-8 and 4-9. Estimated doses and risks for Scenarios 5 and 6, involving the use of phosphogypsum for sediment control, are shown in Tables 4-10 and 4-11. Estimated risks for Scenario 7, based on various phosphogypsum application rates and Ra-226 concentrations, for radon and gamma exposures to the on-site individual are shown in Tables 4-12 and 4-13, respectively; the total risks from both pathways are shown in Table 4-14. The risks shown in the tables are estimated lifetime (70-year) risks from one year of exposure.

As explained in Section 4.3, phosphogypsum applications to agricultural fields are assumed to occur biennially. Equilibrium is reached with competing mechanisms that remove gypsum and its radioactive constituents at 1100 yrs for Ra-226 and 1600 yrs for uranium and thorium. Doses and risks are evaluated for fields that have been repeatedly fertilized on a biennial basis over a 100-year period. Results of Scenarios 1 through 6 are shown for Ra-226 concentrations in phosphogypsum ranging from 26 pCi/g to 3 pCi/g. The actual Ra-226 concentrations in the agricultural fields are lower due to dilution of the phosphogypsum with the soil and depletion mechanisms such as plant uptake and leaching which tend to remove radionuclides.

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Table 4-5. Site-specific input parameters for PATHRAE risk assessments.

Parameter	Units	Clay Value, Sand Value
Phosphogypsum application rate--agricultural scenarios		
Fertilizer--average	MT/acre/yr	0.66
Fertilizer--maximum	MT/acre/yr	2.03
Soil conditioner	MT/acre/yr	4.05
Phosphogypsum application interval--agricultural scenarios	--	biennially
Total years of application--agricultural scenarios	yrs	100
Agricultural field size		
Fertilizer--average	acre	138
Fertilizer--maximum	acre	1,000
Soil conditioner	acre	556
Tillage depth--agricultural scenarios		
Fertilizer--average	m	0.22
Fertilizer-maximum	m	0.46
Soil conditioner	m	0.30
Agricultural field soil density	kg/m^3	1.50E+03
Roadbed material density	kg/m^3	2.25E+03
Distance to nearest residence		
Fertilizer--average	m	890, 100
Fertilizer--maximum	m	6,440, 100
Soil conditioner	m	1,000, 100
Road construction scenarios	m	1,000, 100
Distance to river	m	5.00E+03
River flow rate	m^3/yr	1.00E+08
Density of aquifer	kg/m^3	1.80E+03
Porosity of aquifer	--	0.33
Horizontal velocity of aquifer	m/yr	20

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Table 4-5. Site-specific input parameters for PATHRAE risk assessments (continued).

Parameter	Units	Clay Value, Sand Value
Vertical distance to aquifer		
Fertilizer scenarios	m	3.0
Soil conditioner scenario	m	10.0
Construction scenarios--humid site	m	3.0
Construction scenarios--dry site	m	10.0
Water infiltration rate		
Fertilizer scenarios	m/yr	0.40
Soil conditioner scenario	m/yr	0.25
Construction scenarios--humid site	m/yr	0.40
Construction scenarios--dry site	m/yr	0.25
Fraction of food eaten grown on-site	--	0.50
Adult breathing rate	m^3/yr	8.00E+03
Average dust loading in outside air	kg/m^3	5.00E-07
Average dust loading in R&D lab	kg/m^3	1.00E-07
Atmospheric stability class	--	4
Fraction of time wind blows toward receptor	--	0.093
Average wind speed	m/sec	4.5
Dust resuspension rate for off-site transport	m^3/sec	5.0E-07
Dust deposition velocity	m/sec	1.0E-03
Radon emanating power	--	0.30
Radon diffusion coefficient		
Soil--humid site	m^2/yr	2.2E+01
Soil--dry site	m^2/yr	6.3E+01
Concrete	m^2/yr	1.6E+01
Air change rate in reclaimer house	changes/hr	2
Exposure fraction for indoor exposure	--	0.75
Equivalent exposure fraction for outdoor exposure	--	0.50
Surface erosion rate	m/yr	2.0E-04

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Table 4-5. Site-specific input parameters for PATHRAE risk assessments (continued).

Parameter	Units	Clay Value, Sand Value
Distribution coefficients (K_d)		
Ra-226	m^3/kg	0.45, 0.07
Po-210	m^3/kg	0.50, 0.50
Pb-210	m^3/kg	0.90, 0.90
Th-228	m^3/kg	150.0, 150.0
Ra-228	m^3/kg	0.45, 0.07
Th-230	m^3/kg	150.0, 150.0
Th-232	m^3/kg	150.0, 150.0
U-234	m^3/kg	0.45, 0.07
U-235	m^3/kg	0.45, 0.07
U-238	m^3/kg	0.45, 0.07
Volume of drinking water consumed annually by an individual	m^3/yr	0.37
Length of road perpendicular to aquifer	mile	10
Aquifer thickness	m	10

It is observed that the doses from the groundwater pathways are all zero. As an added sensitivity analysis, scenarios 2, 4, 6, 9 and 11 were created as replicates of 1, 3, 5, 8 and 10, modifying the distance to the offsite individual (100 m). Additionally, the k_d for uranium and radium was reduced to 70 ml/g. Using these modifications, PATHRAE projected a peak risk at year 4200 of 1.5×10^{-8}. These changes also caused, as illustrated in the summary tables, an increase in the risk to members of the CPG from dust inhalation. For a well placed onsite, and a k_d of 70 ml/g for uranium and radium, a risk of 6.7×10^{-9} occurred by the year 1000, for scenario 4. A peak risk of 2×10^{-8} occurred in year 3100 for the same scenario.

For Scenarios 1 and 2, a Ra-226 concentration of 26 pCi/g in phosphogypsum is estimated to correspond to an increase in the soil Ra-226 concentration of 0.60 pCi/g at the end of the 100-year period. For Scenarios 3 and 4, a Ra-226 concentration of 26 pCi/g in phosphogypsum is estimated to correspond to an increase in the soil Ra-226 concentration of 0.88 pCi/g at the end of the 100-year period. For Scenarios 5 and 6, a Ra-226 concentration of 26 pCi/g in phosphogypsum is estimated to correspond to an increase in the soil Ra-226 concentration of 2.70 pCi/g at the end of the 100-year period. As shown in the tables, for each scenario, the doses and risks are directly proportional to the Ra-226 concentration in the original phosphogypsum.

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Table 4-6. Risk assessment results for Scenario 1 - use as fertilizer - average site (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	3.5E+00	1.4E-06	1.4E+00	5.3E-07	9.5E-01	3.7E-07	6.8E-01	2.7E-07	4.1E-01	1.6E-07
Agricultural Worker Dust Inhalation	7.1E-02	5.8E-09	2.7E-02	2.2E-09	1.9E-02	1.6E-09	1.4E-02	1.1E-09	8.2E-03	6.7E-10
On-Site Individual Direct Gamma	7.6E+00	3.0E-06	2.9E+00	1.2E-06	2.0E+00	8.0E-07	1.4E+00	5.7E-07	8.7E-01	3.4E-07
On-Site Individual Indoor Radon	---	2.6E-06	---[c]	1.0E-06	---	6.8E-07	---	5.0E-07	---	3.0E-07
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	7.0E-04	5.7E-11	2.7E-04	2.2E-11	1.9E-04	1.6E-11	1.4E-04	1.1E-11	8.1E-05	6.7E-12
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	4.9E-02	5.2E-09	1.9E-02	2.0E-09	1.3E-02	1.4E-09	9.5E-03	1.5E-09	5.7E-03	3.0E-10
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	8.3E-03	7.4E-10	3.2E-03	2.9E-10	2.2E-03	2.0E-10	1.6E-03	1.4E-10	9.6E-04	8.6E-11

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for at least 100,000 years because of groundwater velocities and retardation factors.

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Table 4-7. Risk assessment results for Scenario 2 - use as fertilizer - average site (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	3.5E+00	1.4E-06	1.4E+00	5.3E-07	9.5E-01	3.7E-07	6.8E-01	2.7E-07	4.1E-01	1.6E-07
Agricultural Worker Dust Inhalation	7.1E-02	5.8E-09	2.7E-02	2.2E-09	1.9E-02	1.6E-09	1.4E-02	1.1E-09	8.2E-03	6.7E-10
On-Site Individual Direct Gamma	7.6E+00	3.0E-06	2.9E+00	1.2E-06	2.0E+00	8.0E-07	1.4E+00	5.7E-07	8.7E-01	3.4E-07
On-Site Individual Indoor Radon	---	2.6E-06	---[c]	1.0E-06	---	6.8E-07	---	5.0E-07	---	3.0E-07
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	4.0E-02	3.3E-09	1.5E-02	1.3E-09	1.1E-02	8.8E-10	7.7E-03	6.3E-10	4.6E-03	3.8E-10
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	4.9E-02	5.2E-09	1.9E-02	2.0E-09	1.3E-02	1.4E-09	9.5E-03	1.5E-09	5.7E-03	3.0E-10
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	8.3E-03	7.4E-10	3.2E-03	2.9E-10	2.2E-03	2.0E-10	1.6E-03	1.4E-10	9.6E-04	8.6E-11

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for about 4,000 years, or the off-site river or well for at least 100,000 years because of groundwater velocities and retardation factors.

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Table 4-8. Risk assessment results for Scenario 3 - use as fertilizer - maximum site (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	5.4E+00	2.2E-06	2.1E+00	8.1E-07	1.5E+00	5.7E-07	1.0E+00	4.1E-07	6.2E-01	2.5E-07
Agricultural Worker Dust Inhalation	1.1E-01	9.0E-09	4.2E-02	3.5E-09	3.0E-02	2.4E-09	2.1E-02	1.7E-09	1.3E-02	1.0E-09
On-Site Individual Direct Gamma	1.2E+01	4.6E-06	4.4E+00	1.8E-06	3.1E+00	1.3E-06	2.2E+00	8.7E-07	1.3E+00	5.2E-07
On-Site Individual Indoor Radon	---	6.8E-06	---[c]	2.6E-06	---	1.8E-06	---	1.3E-06	---	7.5E-07
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	4.4E-05	3.6E-12	1.7E-05	1.4E-12	1.2E-05	9.6E-13	8.5E-06	6.9E-13	5.1E-06	4.1E-13
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	8.6E-02	9.1E-09	3.3E-02	3.5E-09	2.3E-02	2.5E-09	1.6E-02	1.8E-09	9.9E-03	1.1E-09
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	8.8E-02	7.8E-09	3.4E-02	3.0E-09	2.4E-02	2.1E-09	1.7E-02	1.5E-09	1.0E-02	9.1E-10

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

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Table 4-9. Risk assessment results for Scenario 4 - use as fertilizer - maximum site (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	5.4E+00	2.2E-06	2.1E+00	8.1E-07	1.5E+00	5.7E-07	1.0E+00	4.1E-07	6.2E-01	2.5E-07
Agricultural Worker Dust Inhalation	1.1E-01	9.0E-09	4.2E-02	3.5E-09	3.0E-02	2.4E-09	2.1E-02	1.7E-09	1.3E-02	1.0E-09
On-Site Individual Direct Gamma	1.2E+01	4.6E-06	4.4E+00	1.8E-06	3.1E+00	1.3E-06	2.2E+00	8.7E-07	1.3E+00	5.2E-07
On-Site Individual Indoor Radon	---	6.8E-06	---[c]	2.6E-06	---	1.8E-06	---	1.3E-06	---	7.5E-07
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	6.1E-02	5.0E-09	2.3E-02	1.9E-09	1.4E-02	1.4E-09	1.2E-02	9.7E-10	7.0E-03	5.8E-10
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	8.6E-02	9.1E-09	3.3E-02	3.5E-09	2.3E-02	2.5E-09	1.6E-02	1.8E-09	9.9E-03	1.1E-09
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	8.8E-02	7.8E-09	3.4E-02	3.0E-09	2.4E-02	2.1E-09	1.7E-02	1.5E-09	1.0E-02	9.1E-10

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for about 4,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

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Table 4-10. Risk assessment results for Scenario 5 - use as sediment control (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	1.6E+01	6.4E-06	6.3E+00	2.5E-06	4.4E+00	1.8E-06	3.2E+00	1.3E-06	1.9E+00	7.3E-07
Agricultural Worker Dust Inhalation	8.1E-01	6.6E-08	3.1E-01	2.5E-08	2.2E-01	1.8E-08	1.6E-01	1.3E-08	9.3E-02	7.6E-09
On-Site Individual Direct Gamma	3.5E+01	1.4E-05	1.3E+01	5.3E-06	9.4E+00	3.8E-06	6.7E+00	2.7E-06	4.0E+00	1.6E-06
On-Site Individual Indoor Radon	---	1.2E-05	---[c]	4.7E-06	---	3.3E-06	---	2.4E-06	---	1.4E-06
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	6.6E-03	5.4E-10	2.5E-03	2.1E-10	1.8E-03	1.5E-10	1.3E-03	1.0E-10	7.6E-04	6.2E-11
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	2.2E-01	2.3E-08	8.4E-02	9.0E-09	5.9E-02	6.3E-09	4.2E-02	4.5E-09	2.5E-02	2.7E-09
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	1.5E-01	1.3E-08	5.8E-02	5.1E-09	4.1E-02	3.6E-09	2.9E-02	2.6E-09	1.8E-02	1.5E-09

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

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Table 4-11. Risk assessment results for Scenario 6 - use as sediment control (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	1.6E+01	6.4E-06	6.3E+00	2.5E-06	4.4E+00	1.8E-06	3.2E+00	1.3E-06	1.9E+00	7.3E-07
Agricultural Worker Dust Inhalation	8.1E-01	6.6E-08	3.1E-01	2.5E-08	2.2E-01	1.8E-08	1.6E-01	1.3E-08	9.3E-02	7.6E-09
On-Site Individual Direct Gamma	3.5E+01	1.4E-05	1.3E+01	5.3E-06	9.4E+00	3.8E-06	6.7E+00	2.7E-06	4.0E+00	1.6E-06
On-Site Individual Indoor Radon	---	1.2E-05	---[c]	4.7E-06	---	3.3E-06	---	2.4E-06	---	1.4E-06
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	4.5E-01	3.7E-08	1.7E-01	1.4E-08	1.2E-01	9.9E-09	8.7E-02	7.1E-09	5.2E-02	4.3E-09
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	2.2E-01	2.3E-08	8.4E-02	9.0E-09	5.9E-02	6.3E-09	4.2E-02	4.5E-09	2.5E-02	2.7E-09
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	1.5E-01	1.3E-08	5.8E-02	5.1E-09	4.1E-02	3.6E-09	2.9E-02	2.6E-09	1.8E-02	1.5E-09

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for about 4,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

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Table 4-12. Risk assessment results for Scenario 7 - radon exposure risks to the on-site individual as a function of phosphogypsum application rate and Ra-226 concentration.[a]

Application Rate (lbs/Acre)	Ra-226 Concentration in Phosphogypsum (pCi/g)						
	3	7	15	20	30	45	60
500	1.0E-07	2.4E-07	5.1E-07	6.8E-07	1.0E-06	1.6E-06	2.1E-06
1,000	2.1E-07	4.8E-07	1.0E-06	1.4E-06	2.1E-06	3.1E-06	--
1,500	3.1E-07	7.5E-07	1.6E-06	2.1E-06	3.1E-06	--	--
2,500	5.1E-07	1.2E-06	2.6E-06	3.4E-06	--	--	--
5,000	1.0E-06	2.4E-06	5.1E-06	--	--	--	--
10,000	2.1E-06	4.8E-06	1.0E-05	--	--	--	--

[a] Lifetime risk from one year of exposure.

Table 4-13. Risk assessment results for Scenario 7 - external gamma risks to the on-site individual as a function of phosphogypsum application rate and Ra-226 concentration.[a]

Application Rate (lbs/Acre)	Ra-226 Concentration in Phosphogypsum (pCi/g)						
	3	7	15	20	30	45	60
500	1.1E-07	2.6E-07	5.7E-07	7.5E-07	1.1E-06	1.7E-06	2.3E-06
1,000	2.3E-07	5.3E-07	1.1E-06	1.5E-06	2.3E-06	3.4E-06	--
1,500	3.4E-07	7.9E-07	1.7E-06	2.3E-06	3.4E-06	--	--
2,500	5.7E-07	1.3E-06	2.8E-06	3.8E-06	--	--	--
5,000	1.1E-06	2.6E-06	5.7E-06	--	--	--	--
10,000	2.3E-06	5.3E-06	1.1E-05	--	--	--	--

[a] Lifetime risk from one year of exposure.

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Table 4-14. Risk assessment results for Scenario 7 - Total risks to the on-site individual as a function of phosphogypsum application rate and Ra-226 concentration.[a,b]

Application Rate (lbs/Acre)	Ra-226 Concentration in Phosphogypsum (pCi/g)						
	3	7	15	20	30	45	60
500	2.2E-07	5.1E-07	1.1E-06	1.4E-06	2.2E-06	3.3E-06	4.4E-06
1,000	4.4E-07	1.0E-06	2.2E-06	2.9E-06	4.4E-06	6.5E-06	--
1,500	6.5E-07	1.4E-06	3.3E-06	4.4E-06	6.5E-06	--	--
2,500	1.1E-06	2.5E-06	5.4E-06	7.2E-06	--	--	--
5,000	2.2E-06	5.1E-06	1.1E-05	--	--	--	--
10,000	4.4E-06	1.0E-05	2.2E-05	--	--	--	--

(a) Lifetime risk from one year of exposure.

(b) The sum of the risks from Tables 4-12 and 4-13.

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For each of the agricultural scenarios, the highest doses and risks result from external gamma exposure and from indoor radon inhalation to the on-site individual. For Scenario 1, the lifetime risk to the on-site individual from one year of external gamma exposure is estimated to range from 3.0×10^{-6} for 26 pCi/g phosphogypsum to 3.4×10^{-7} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 2.6×10^{-6} for 26 pCi/g phosphogypsum to 3.0×10^{-7} for 3 pCi/g phosphogypsum.

For Scenario 3, the lifetime risk to the on-site individual from one year of external gamma exposure is estimated to range from 4.6×10^{-6} for 26 pCi/g phosphogypsum to 5.2×10^{-7} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 6.8×10^{-6} for 26 pCi/g phosphogypsum to 7.5×10^{-7} for 3 pCi/g phosphogypsum.

For Scenario 5, the lifetime risk to the on-site individual from one year of external gamma exposure is estimated to range from 1.4×10^{-5} for 26 pCi/g phosphogypsum to 1.6×10^{-6} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 1.2×10^{-5} for 26 pCi/g phosphogypsum to 1.4×10^{-6} for 3 pCi/g phosphogypsum.

The results of the first four scenarios prompted Scenario 7; an evaluation of the risks associated with the two principal exposure pathways, radon and direct gamma exposures, with varying phosphogypsum application rates and Ra-226 concentrations. Combinations of application rates and Ra-226 concentrations varied from 500 to 10,000 lbs/acre and 3 to 60 pCi/g, respectively. The affect of these two variables on the estimated risk is best illustrated by the family of curves represented in Figures 4-2 to 4-4, which illustrate the increase in risk as the Ra-226 concentrations increase with each application rate. The risks presented in the figures are those listed in Tables 4-12 to 4-14 multiplied by a 70-year exposure period. Thus, they represent the estimated lifetime risk resulting from a 70-year exposure. The total lifetime risk to the on-site individual from 70 years of external gamma and radon exposures is estimated to range from 1.5×10^{-5} for 3 pCi/g phosphogypsum applied at a rate of 500 lbs/acre to 1.5×10^{-3} for 15 pCi/g phosphogypsum applied at a rate of 10,000 lbs/acre. Using Scenario 7, the combinations of phosphogypsum application rates and Ra-226 concentrations that yield an estimated lifetime risk of 3×10^{-4} is plotted in Figure 4-5. For example, a lifetime risk of 3×10^{-4} will result when phosphogypsum, containing 1 pCi/g of Ra-226, is applied at a rate of 25,000 lbs/acre; whereas, to produce the same risk when the application rate is 1,000 lbs/acre will require a Ra-226 concentration of 30 pCi/g.

4.4.2 Phosphogypsum in Road Construction

The road construction scenarios evaluated in this risk assessment are shown schematically in Figure 4-1. The results of the risk assessment of the use of phosphogypsum in road construction are summarized in Tables 4-15 to 4-18. Estimated doses and risks for Scenarios 8 and 9, involving the use of phosphogypsum in a road base, are shown in Tables

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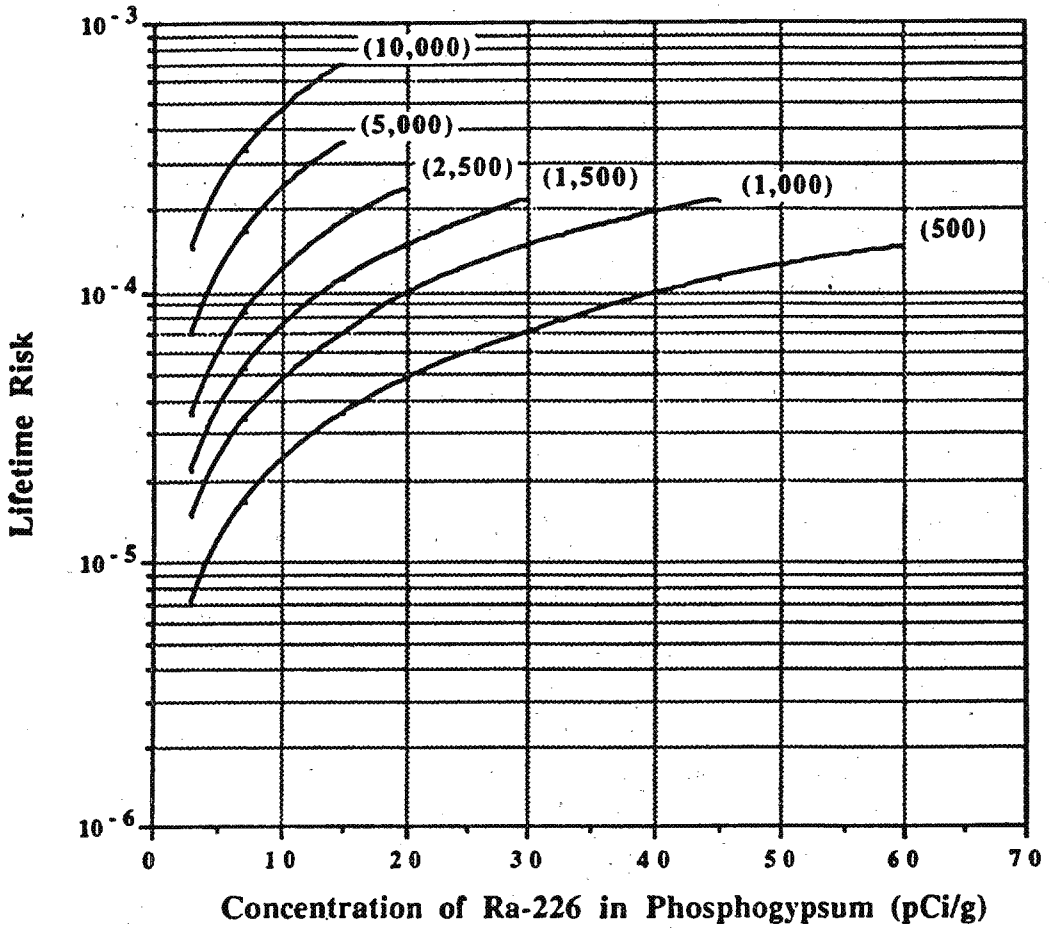

Figure 4-2. Risk assessment results for Scenario 7 - radon exposure risks to the on-site individual as a function of the Ra-226 content of phosphogypsum for the six application rates (lbs/acre) shown in parenthesis

ED_005285_00000283-00068

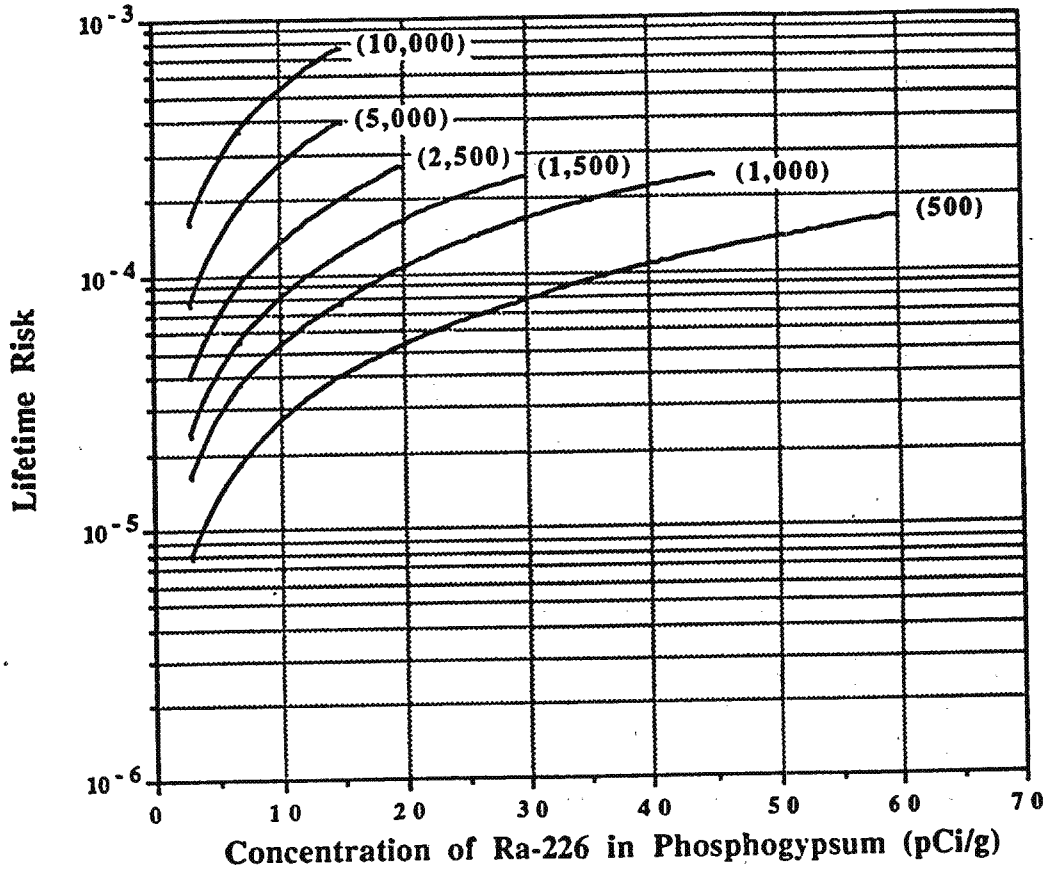

Figure 4-3. Risk assessment results for Scenario 7 - external gamma exposure risks to the on-site individual as a function of the Ra-226 content of phosphogypsum for the six application rates (lbs/acre) shown in parenthesis

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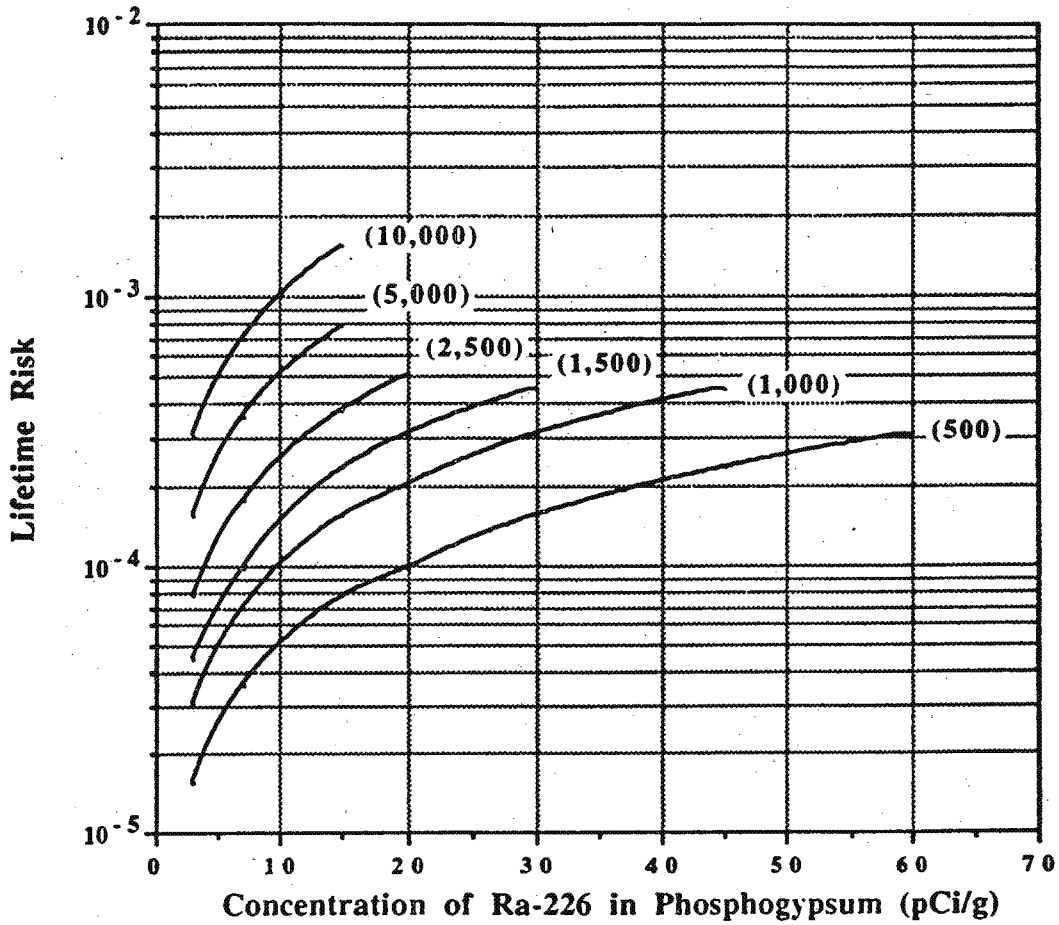

Figure 4-4. Risk assessment results for Scenario 7 - total radon and gamma exposure risks to the on-site individual as a function of the Ra-226 content of phosphogypsum for the six application rates (lbs/acre) shown in paraenthesis

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Figure 4-5. Application rate of phosphogypsum as a function of Ra-226 concentration for a lifetime risk of $3x10^{-4}$.

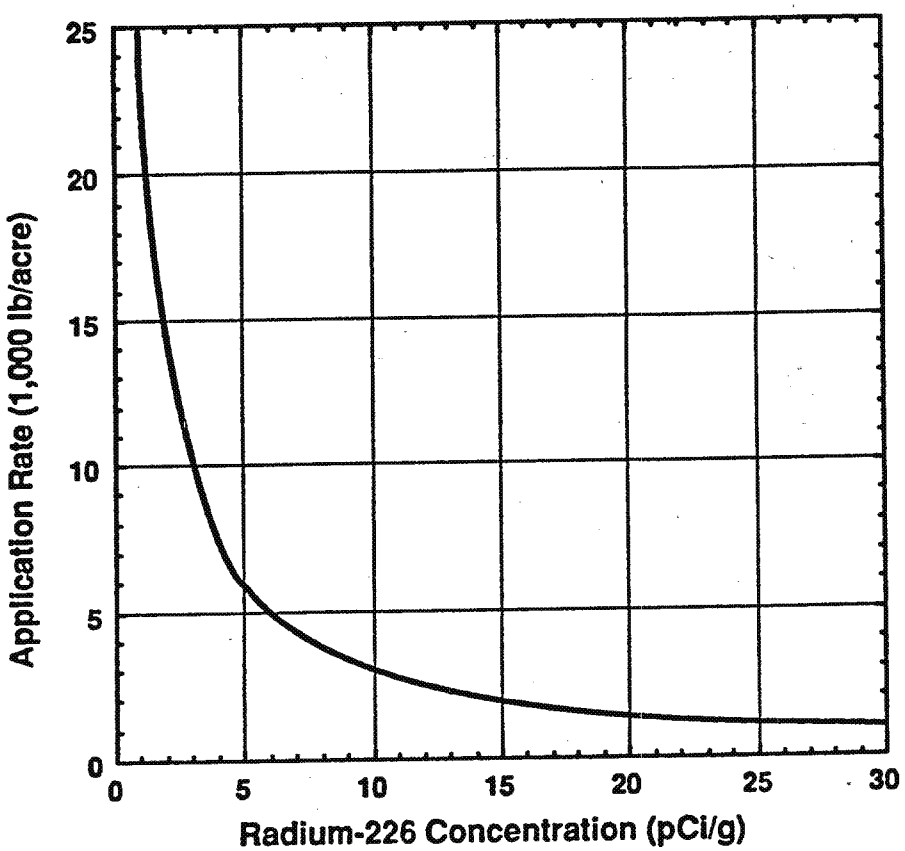

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Table 4-15. Risk assessment results for Scenario 8 - use of phosphogypsum in road base for secondary road (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Construction Worker -No Shielding- Direct Gamma	4.1E+01	1.5E-05	1.6E+01	5.9E-06	1.1E+01	4.1E-06	7.9E+00	3.0E-06	4.7E+00	1.8E-06
Construction Worker -With Shielding- Direct Gamma	2.5E+01	9.0E-06	9.4E+00	3.5E-06	6.6E+00	2.5E-06	4.7E+00	1.8E-06	2.8E+00	1.1E-06
Construction Worker -Humid Site- Dust Inhalation	1.0E+00	8.4E-08	3.8E-01	3.1E-08	2.7E-01	2.2E-08	1.9E-01	1.6E-08	1.2E-01	9.4E-09
Construction Worker -Dry Site- Dust Inhalation	2.5E+00	2.2E-07	9.6E-01	8.3E-08	6.7E-01	5.8E-08	4.8E-01	4.2E-08	2.9E-01	2.5E-08
Person Driving on Road Direct Gamma	2.2E-01	8.2E-08	8.4E-02	3.1E-08	5.8E-02	2.2E-08	4.2E-02	1.5E-08	2.5E-02	9.6E-09
Member of CPG Direct Gamma	4.3E-02	1.6E-08	1.6E-02	6.2E-09	1.2E-02	4.4E-09	8.2E-03	3.2E-09	4.9E-03	1.9E-09
Member of CPG - Ingestion of Drinking Water From Contaminated Well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of Foodstuff Contaminated by Well Water	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer Direct Gamma	7.1E+01	2.6E-05	2.7E+01	1.0E-05	1.9E+01	7.2E-06	1.4E+01	5.3E-06	8.2E+00	3.2E-06
Reclaimer -Humid Site- Indoor Radon Inhalation	---	5.9E-05	---	2.2E-05	---	1.6E-05	---	1.1E-05	---	6.8E-06
Reclaimer -Dry Site- Indoor Radon Inhalation	---	6.2E-05	---	2.4E-05	---	1.7E-05	---	1.2E-05	---	7.5E-06
Reclaimer Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer - Ingestion of Foodstuff Grown On-Site	2.6E-01	1.5E-08	1.0E-01	5.9E-09	6.8E-02	4.2E-09	4.7E-02	3.0E-09	2.9E-02	1.8E-09
Individual - Ingestion of River Water Contaminated by Groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of River Water Contaminated by Surface Runoff	2.0E-02	1.5E-09	7.6E-03	5.6E-10	5.3E-03	4.0E-10	3.8E-03	2.7E-10	2.3E-03	1.7E-10

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

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Table 4-16. Risk assessment results for Scenario 9 - use of phosphogypsum in road base for secondary road (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Construction Worker -No Shielding- Direct Gamma	4.1E+01	1.5E-05	1.6E+01	5.9E-06	1.1E+01	4.1E-06	7.9E+00	3.0E-06	4.7E+00	1.8E-06
Construction Worker -With Shielding- Direct Gamma	2.5E+01	9.0E-06	9.4E+00	3.5E-06	6.6E+00	2.5E-06	4.7E+00	1.8E-06	2.8E+00	1.1E-06
Construction Worker -Humid Site- Dust Inhalation	1.0E+00	8.4E-08	3.8E-01	3.1E-08	2.7E-01	2.2E-08	1.9E-01	1.6E-08	1.2E-01	9.4E-09
Construction Worker -Dry Site- Dust Inhalation	2.5E+00	2.2E-07	9.6E-01	8.3E-08	6.7E-01	5.8E-08	4.8E-01	4.2E-08	2.9E-01	2.5E-08
Person Driving on Road Direct Gamma	2.2E-01	8.2E-08	8.4E-02	3.1E-08	5.8E-02	2.2E-08	4.2E-02	1.5E-08	2.5E-02	9.6E-09
Member of CPG Direct Gamma	4.3E-02	1.6E-08	1.6E-02	6.2E-09	1.2E-02	4.4E-09	8.2E-03	3.2E-09	4.9E-03	1.9E-09
Member of CPG - Ingestion of Drinking Water From Contaminated Well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of Foodstuff Contaminated by Well Water	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer Direct Gamma	7.1E+01	2.6E-05	2.7E+01	1.0E-05	1.9E+01	7.2E-06	1.4E+01	5.3E-06	8.2E+00	3.2E-06
Reclaimer -Humid Site- Indoor Radon Inhalation	---	5.9E-05	---	2.2E-05	---	1.6E-05	---	1.1E-05	---	6.8E-06
Reclaimer -Dry Site- Indoor Radon Inhalation	---	6.2E-05	---	2.4E-05	---	1.7E-05	---	1.2E-05	---	7.5E-06
Reclaimer Well Water Use	4.2E-03	4.2E-10	1.6E-03	1.6E-10	1.1E-03	1.1E-10	8.1E-04	8.0E-11	4.8E-04	4.8E-11
Reclaimer - Ingestion of Foodstuff Grown On-Site	2.6E-01	1.5E-08	1.0E-01	5.9E-09	6.8E-02	4.2E-09	4.7E-02	3.0E-09	2.9E-02	1.8E-09
Individual - Ingestion of River Water Contaminated by Groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of River Water Contaminated by Surface Runoff	2.0E-02	1.5E-09	7.6E-03	5.6E-10	5.3E-03	4.0E-10	3.8E-03	2.7E-10	2.3E-03	1.7E-10

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the off-site river or well via the groundwater pathway for more than 10,000 years because of groundwater velocities and retardation factors.

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Table 4-17. Risk assessment results for Scenario 10 - use of phosphogypsum in a concrete road surface (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Construction Worker -No Shielding- Direct Gamma	4.1E+01	1.5E-05	1.6E+01	5.9E-06	9.1E+00	4.1E-06	7.9E+00	3.0E-06	4.7E+00	1.8E-06
Construction Worker -With Shielding- Direct Gamma	2.5E+01	9.0E-06	9.4E+00	3.5E-06	5.5E+00	2.5E-06	4.7E+00	1.8E-06	2.8E+00	1.1E-06
Construction Worker -Humid Site- Dust Inhalation	1.0E+00	8.4E-08	3.8E-01	3.1E-08	2.7E-01	2.2E-08	1.9E-01	1.6E-08	1.2E-01	9.4E-09
Construction Worker -Dry Site- Dust Inhalation	2.5E+00	2.2E-07	9.6E-01	8.3E-08	6.7E-01	5.8E-08	4.8E-01	4.2E-08	2.9E-01	2.5E-08
Person Driving on Road Direct Gamma	2.6E+00	9.6E-07	9.8E-01	3.7E-07	6.9E-01	2.6E-07	4.9E-01	1.8E-07	2.9E-01	1.1E-07
Member of CPG Direct Gamma	5.0E-01	1.8E-07	1.9E-01	7.3E-08	1.3E-01	5.1E-08	9.7E-02	3.6E-08	5.8E-02	2.2E-08
Member of CPG - Ingestion of Drinking Water From Contaminated Well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of Foodstuff Contaminated by Well Water	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer Direct Gamma	1.4E+02	5.1E-05	5.2E+01	1.9E-05	3.7E+01	1.4E-05	2.6E+01	1.0E-05	1.6E+01	5.9E-06
Reclaimer -Humid Site- Indoor Radon Inhalation	---	6.8E-05	---	2.7E-05	---	1.9E-05	---	1.4E-05	---	8.1E-06
Reclaimer -Dry Site- Indoor Radon Inhalation	---	8.1E-05	---	3.1E-05	---	2.2E-05	---	1.6E-05	---	9.3E-06
Reclaimer Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer -Ingestion of Foodstuff Grown on-Site	2.6E-01	1.5E-08	1.0E-01	5.9E-09	6.8E-02	4.2E-09	4.7E-02	3.0E-09	2.9E-02	1.8E-09
Individual -Ingestion of River Water Contaminated by Groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual -Ingestion of River Water Contaminated by Surface Runoff	2.0E-02	1.5E-09	7.6E-03	5.6E-10	5.3E-03	4.0E-10	3.8E-03	2.7E-10	2.3E-03	1.7E-10

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

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Table 4-18. Risk assessment results for Scenario 11 - use of phosphogypsum in a concrete road surface (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Construction Worker -No Shielding- Direct Gamma	4.1E+01	1.5E-05	1.6E+01	5.9E-06	9.1E+00	4.1E-06	7.9E+00	3.0E-06	4.7E+00	1.8E-06
Construction Worker -With Shielding- Direct Gamma	2.5E+01	9.0E-06	9.4E+00	3.5E-06	5.5E+00	2.5E-06	4.7E+00	1.8E-06	2.8E+00	1.1E-06
Construction Worker -Humid Site- Dust Inhalation	1.0E+00	8.4E-08	3.8E-01	3.1E-08	2.7E-01	2.2E-08	1.9E-01	1.6E-08	1.2E-01	9.4E-09
Construction Worker -Dry Site- Dust Inhalation	2.5E+00	2.2E-07	9.6E-01	8.3E-08	6.7E-01	5.8E-08	4.8E-01	4.2E-08	2.9E-01	2.5E-08
Person Driving on Road Direct Gamma	2.6E+00	9.6E-07	9.8E-01	3.7E-07	6.9E-01	2.6E-07	4.9E-01	1.8E-07	2.9E-01	1.1E-07
Member of CPG Direct Gamma	5.0E-01	1.8E-07	1.9E-01	7.3E-08	1.3E-01	5.1E-08	9.7E-02	3.6E-08	5.8E-02	2.2E-08
Member of CPG - Ingestion of Drinking Water From Contaminated Well	—[c]	—[c]	—	—	—	—	—	—	—	—
Member of CPG - Ingestion of Foodstuff Contaminated by Well Water	—[c]	—[c]	—	—	—	—	—	—	—	—
Reclaimer Direct Gamma	1.4E+02	5.1E-05	5.2E+01	1.9E-05	3.7E+01	1.4E-05	2.6E+01	1.0E-05	1.6E+01	5.9E-06
Reclaimer -Humid Site- Indoor Radon Inhalation	—	6.8E-05	—	2.7E-05	—	1.9E-05	—	1.4E-05	—	8.1E-06
Reclaimer -Dry Site- Indoor Radon Inhalation	—	8.1E-05	—	3.1E-05	—	2.2E-05	—	1.6E-05	—	9.3E-06
Reclaimer Well Water Use	4.2E-03	4.2E-10	1.6E-03	1.6E-10	1.1E-03	1.1E-10	8.1E-04	8.0E-11	4.8E-04	4.8E-11
Reclaimer -Ingestion of Foodstuff Grown on-Site	2.6E-01	1.5E-08	1.0E-01	5.9E-09	6.8E-02	4.2E-09	4.7E-02	3.0E-09	2.9E-02	1.8E-09
Individual -Ingestion of River Water Contaminated by Groundwater	—[c]	—[c]	—	—	—	—	—	—	—	—
Individual -Ingestion of River Water Contaminated by Surface Runoff	2.0E-02	1.5E-09	7.6E-03	5.6E-10	5.3E-03	4.0E-10	3.8E-03	2.7E-10	2.3E-03	1.7E-10

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the off-site river or well via the groundwater pathway for more than 10,000 years because of groundwater velocities and retardation factors.

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4-15 and 4-16. Estimated doses and risks for Scenarios 10 and 11, involving the use of phosphogypsum in both a concrete road surface and a road base, are shown in Tables 4-17 and 4-18.

In evaluating the risk to the construction worker from external gamma radiation, four cases were analyzed -- two in which the worker stands directly on the roadbed for the entire work day (no shielding), and two in which the worker uses equipment, such as a road grader, which provides some protection from external gamma radiation (with shielding). These four cases are considered to bracket the worker doses which could be received from external gamma radiation. Worker doses for Scenarios 8 and 9 were evaluated for the case of no asphalt cover over the roadbed to maximize the results of the dose calculations. Worker doses from dust inhalation were evaluated for a humid site (with characteristics typical of a southeastern site) and a dry site (with characteristics typical of a southwestern site).

Reclaimer doses were evaluated for a time (presumed to be 50 years after road construction) when the road is closed and the road surface has crumbled and been removed. The reclaimer is assumed to live in a house constructed on the site and to obtain 50 percent of his food from a garden grown on the site. Indoor radon doses to the reclaimer were evaluated for both a humid site and a dry site.

For the road construction scenarios, the highest doses and risks result from external gamma exposure and indoor radon inhalation to the reclaimer. For Scenarios 8 and 9, the lifetime risk to the reclaimer from one year of external gamma exposure is estimated to range from 2.6×10^{-5} for 26 pCi/g phosphogypsum to 3.2×10^{-6} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 6.2×10^{-5} for 26 pCi/g phosphogypsum to 7.5×10^{-6} for 3 pCi/g phosphogypsum.

For Scenarios 10 and 11, the lifetime risk to the reclaimer from one year of external gamma exposure is estimated to range from 5.1×10^{-5} for 26 pCi/g phosphogypsum to 5.9×10^{-6} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 8.1×10^{-5} for 26 pCi/g phosphogypsum to 9.3×10^{-6} for 3 pCi/g phosphogypsum.

4.4.3 Phosphogypsum in Research & Development Activities

The results of the risk assessment of the use of phosphogypsum in Research & Development activities are summarized in Table 4-19. For the Research & Development scenario (Scenario 12), a researcher is postulated to work in a laboratory and be exposed to an open 55-gallon drum of phosphogypsum. Doses to the researcher from external gamma radiation, dust inhalation, and indoor radon inhalation are evaluated.

The doses and risks to the researcher from external gamma radiation and dust inhalation are estimated to be comparable to worker doses from the agricultural and road

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Table 4-19. Risk assessment results for Scenario 12 - use of phosphogypsum in R&D activities.

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Researcher Direct Gamma	2.5E+00	9.1E-07	9.6E-01	3.5E-07	6.7E-01	2.5E-07	4.8E-01	1.8E-07	2.9E-01	1.1E-07
Researcher Dust Inhalation	9.1E-01	8.3E-08	3.5E-01	3.2E-08	2.5E-01	2.2E-08	1.8E-01	1.6E-08	1.1E-01	9.6E-09
Researcher Indoor Radon Inhalation	---	2.1E-05	---	8.1E-06	---	5.6E-06	---	4.0E-06	---	2.4E-06

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.

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construction scenarios. The greatest risk to the researcher is estimated to be from indoor radon inhalation. The indoor radon inhalation risk is estimated to range from 2.1×10^{-5} for 26 pCi/g phosphogypsum to 2.4×10^{-6} for 3 pCi/g phosphogypsum.

4.4.4 Ingestion of Treated Soil

A final risk assessment was conducted of ingesting soil that had been treated with phosphogypsum. Two scenarios are considered: Scenario 13, which assumes a biennial application rate for 100 years of 664 kg/acre of phosphogypsum containing 10 pCi/g Ra-226, and scenario 14, which assumes an initial application of 8,000 kg/acre of phosphogypsum containing 26 pCi/g Ra-226 followed by biennial applications of 4,000 kg/acre for 100 years. These application rates are the same as those used for scenarios 1/2 and 5/6, respectively (see Section 4.3.3.1). The detailed calculations and the results of this risk assessment are provided in Appendix C. The exposure periods and soil ingestion rates selected for this assessment are also listed in Appendix C.

The total estimated risks for each scenario are given in Table 4-20. The estimated risks from ingesting treated soil are small in comparison to those estimated earlier in this section for exposure to either direct gamma radiation or indoor radon-222. As might be expected, the highest estimated lifetime risk, 7.4E-6, is for a 70-year exposure period combined with using the phosphogypsum containing the highest Ra-226 concentration, 26 pCi/g. This risk is similar to that estimated for exposure to either direct gamma radiation or indoor radon when phosphogypsum containing only 3 pCi/g Ra-226 is applied at a rate of 227 kg (500 lbs) per acre (see Tables 4-12 and 4-13). Over 85 percent of the total risk is due to the presence of Pb-210 and Po-210, while the Ra-226 present contributes only about 10 percent of the risk.

Table 4-20. The estimated total risks due to the ingestion of soil treated with phosphogypsum[a].

Condition	Exposure Period[b]		
	70 year	30 year	9 year
Scenario 13	1.9E-6	8.8E-7	3.7E-7
Scenario 14	7.4E-6	3.5E-6	1.5E-6

(a) Results from Appendix C.
(b) Lifetime risk for the specified exposure period.

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5. AVAILABILITY AND COSTS OF COMPETING MATERIALS

5.1 PEANUT FARMING IN GEORGIA

5.1.1 Availability

Georgia grows almost half of the peanuts produced in the United States. Of the more than 600,000 acres of peanuts grown in Georgia, approximately a third require some form of gypsum. Traditionally, 60-70% of that demand has been supplied by phosphogypsum (GDA90). But since the ban on phosphogypsum, there have been numerous entrants into the Georgia market for gypsum materials, even though there have been waivers for the agricultural use of phosphogypsum. New products in the Georgia area include: Nutcracker--a by-product of sulfuric acid neutralization distributed out of Tampa, Florida; Kemira--an industrial acid neutralization product distributed out of Savannah, Georgia; and Fluorolite--another acid neutralization product distributed out of Louisiana and Alabama. According to Agrobusiness, one of the largest distributors of gypsum materials in Georgia, these new products, as well as pure gypsum products, are abundant and available in the Georgia peanut growing area (JA91).

5.1.2 Cost

Dr. Carley, an agricultural economist at the University of Georgia, presented cost and effectiveness data for different types of gypsum fertilizers, including phosphogypsum, during public testimony on the limited reconsideration and proposed rule NESHAP for radionuclide emissions from phosphogypsum stacks in May 1990. He compared the four phosphate fertilizers in Table 5-1 with a control (no gypsum material added) to determine the economic return when using the four different types of gypsum materials. Carley found that phosphogypsum gave the highest return at $1218 per acre. U.S.G. 500, a gypsum product still available on the Georgia market today, provided a slightly lower return of $1212 per acre. The other two products analyzed, granular and pelleted substances, gave significantly lower returns.

By analyzing Dr. Carley's information, it is possible to compare the cost of increasing peanut yield from the control level for each of the gypsum materials. This comparison is shown in Table 5-2. Phosphogypsum provides the lowest cost per pound of peanuts when increasing yield. Gypsum costs are 1 cent for every pound of increased peanut yield if phosphogypsum is used as the source of gypsum. It costs four times as much, 4 cents per pound, to increase crop yield using U.S.G. 500. The two other materials, granular and pelleted substances, have considerably higher costs per pound to provide an increased yield.

Further analysis of phosphogypsum cost compared to substitutes is presented in Table 5-3. The analysis makes no assumption about comparative yield when using one gypsum fertilizer or another. It presents cost indices for gypsum materials competitive with phosphogypsum. Only two products, Fluorolite and Nutcracker have indices less than 1.

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Table 5-1. Pod yields per acre of peanuts for various gypsum materials, estimated cost of various materials and estimated net return, Georgia.

Gypsum Material[a]	Experimental Yields (pds/acre)[a]	Gross Return ($/acre)[b]	Cost of Gypsum Material ($/acre)[c]	Return Minus Gypsum Cost ($/acre)
Control (no gypsum material)	2708	854	0	854
Phosphogypsum - Occiwet.	3917	1236	17.5	1218
Crystalline - U.S.G. 500	4000	1262	50	1212
Granular - Abssgram	3091	975	45	930
Pelleted - Abpellet	2768	873	37.5	835

(a) From reference Al89.

(b) Priced at 1990 quota support price of $631 per ton, no adjustment made for grade.

(c) Based on Carley's personal communication with Coastal Plain Experimental Station research personnel; 1990 price quotations. Costs include transportation costs to Tift County Georgia.

Kemira is identically priced to phosphogypsum, with a cost index of 1. All of the other gypsum products are at least two and one-half times as expensive as phosphogypsum, with cost indices of 2.69 or greater. These cost indices are misleading, however, because they do not include transportation costs in the cost of the fertilizer. The two products which seem most competitive with phosphogypsum are both produced great distances from the Georgia peanut growing district -- in Tampa, Florida and Geismar, Louisiana. The Table 5-3 cost indices were revised by including estimated transportation costs from the point of sale to Tifton, Georgia for each of the fertilizers. The new cost indices are shown in Table 5-4. Tifton, Georgia was chosen as the final destination for determining transportation costs because it is in the center of the Georgia peanut growing area. The revised fertilizer cost indices show that no gypsum treatments are less expensive than phosphogypsum. Only Kemira, with a cost index of 1.28 approaches phosphogypsum. All other applications cost at least twice as much as phosphogypsum, with the exception of A.C.G.2000 and Nutcracker which cost 1.86 and 1.95 times as much as phosphogypsum, respectively.

As different soil amendments are not applied at the same rate, the application rate should be considered in the comparative pricing of different products. For example, the University of Georgia Cooperative Extension Service recommends a minimum application

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Table 5-2. Gypsum material cost per pound of peanuts for competing gypsum materials.

Gypsum Material	Cost of Material ($/acre)	Experimental Yield (pds/acre)	Change in Cost From Control ($)	Change in Yield From Control (pds)	Change in Cost/Change in Yield ($/pd)
None (Control)	0	2708			
Phosphogypsum - Occiwet.	17.5	3917	17.5	1209	0.01
Crystalline - U.S.G. 500	50	4000	50	1292	0.04
Granular - Abssgram	45	3091	45	383	0.12
Pelleted - Abpellet	37.5	2768	37.5	60	0.63

Source: Table 5.1

Table 5-3. Fertilizer cost indices for competing materials relative to phosphogypsum at point of sale.

Fertilizer		Point of Sale[a]	Price at Point of Sale ($/ton)[b]	Fertilizer Cost Index
Phosphogypsum		White Springs, FL	13	1.00
U.S.G. 500		Brunswick, GA	38	2.92
Gold Bond Bag	(bagged)	Savannah, GA	41.5	3.19
	(bulk)	Savannah, GA	35	2.69
Domtar	(bagged)	Savannah, GA	47	3.62
	(bulk)	Savannah, GA	35	2.69
A.C.G. 2000		Cordele, GA	40	3.08
Nutcracker		Tampa, FL	10	0.77
Kemira		Savannah, GA	13	1.00
Fluorolite		Geismar, LA	7.5	0.58
		Columbia, AL	47	3.62
Granular (made from Kemira		Moultrie, GA	63	4.85
by Florida Favorites)		Macon, GA	63	4.85

(a) Prices obtained from a phone conversation with Jim Arnold of Agrobusiness in Albany, Georgia on August 13, 1991.

(b) The fertilizer cost does not include equipment and labor cost for applying the fertilizer or transportation costs to the farm. Equipment costs can be considered the same for all fertilizers, but labor costs are higher for the two dry gypsums, Gold Bond Bag and Domtar, than for the damp gypsums.

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Table 5-4. Fertilizer cost indices for competing materials relative to phosphogypsum incorporating transportation costs into the fertilizer cost.

Fertilizer		Point of Sale	Miles From Point of Sale to Tifton, GA[a]	Transportation Cost ($/ton)[b]	Total Fertilizer Cost (Transportation & Sale) ($/ton)	Fertilizer Cost Index
Phosphogypsum		White Springs, FL	107	10.7	23.7	1.00
U.S.G. 500		Brunswick, GA	111	11.1	49.1	2.07
Gold Bond Bag	(bagged)	Savannah, GA	174	17.4	58.9	2.49
	(bulk)	Savannah, GA	174	17.4	52.4	2.21
Domtar	(bagged)	Savannah, GA	174	17.4	64.4	2.72
	(bulk)	Savannah, GA	174	17.4	52.4	2.21
A.C.G. 2000		Cordele, GA	40	4	44	1.86
Nutcracker		Tampa, FL	363	36.3	46.3	1.95
Kemira		Savannah, GA	174	17.4	30.4	1.28
Fluorolite		Geismar, LA	400	40	47.5	2.00
		Columbia, AL	107	10.7	57.7	2.43
Granular (made from Kemira		Moultrie, GA	29	2.9	65.9	2.78
by Florida Favorites)		Macon, GA	104	10.4	73.4	3.10

(a) Miles determined from a 1989 Rand McNally Road Atlas.

(b) Transportation Costs determined based on an estimated truck freight rate of $.10/ton/mile. The estimate is derived from the truck freight rate of Exhibit 2.6 of "Transportation Benefits of The Proposed Wabash Waterway," completed by Jack Faucett Associates in December of 1986. The figure was revised to account for inflation.

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rate (broadcasting) for phosphogypsum and USG 500 of 1000 lbs/acre and 750 lbs/acre, respectively (USG90). Thus, a complete comparative pricing for phosphogypsum and substitute products will include their respective application rates. Table 5-5 presents the results of such an analysis for phosphogypsum and three substitute materials. It is estimated that USG 500 will cost $6.56 (about 55 percent) more per acre than phosphogypsum. Gold Bond and Kemira are 132 and 150 percent more costly per acre, respectively, than phosphogypsum.

Table 5-5. The comparison of material costs per acre.

Material	Costs (dollars/ton)		Application Rates (lbs/acre) (USG90)	Cost ($/acre)	Cost/Acre Differential ($)
	Product (Table 5-3)	Transportation (Table 5-4)			
Phosphogypsum	13	10.70	1000	11.85	0
USG500	38	11.10	750	18.41	6.56
Gold Bond	35	17.40	1050	27.51	15.66
Kemira	63	2.90	900	29.66	17.81

5.2 PEANUT FARMING IN NORTH CAROLINA

The North Carolina Agricultural Extension Service recommends that gypsum be applied to all peanuts regardless of soil type or soil nutrient levels. Although soil calcium is usually sufficient for good plant growth, it is inadequate for pod development and good quality peanuts. Application rates are balanced with the calcium content of the gypsum. Table 5-6 provides the application rates recommended by the North Carolina Agricultural Extension Service for four forms of gypsum (NC90).

According to the Department of Agriculture of the State of North Carolina, approximately two-thirds of peanut growers used phosphogypsum on crops in 1990. They estimate that the banning of phosphogypsum for agriculture use on peanuts would cost North Carolina peanut farmers approximately $2 million per year in producing 160,000 acres of peanuts (Gr90). In March 1991, the North Carolina Peanut Growers Association wrote that other gypsum sources may be available in North Carolina, but that "Phosphogypsum is less expensive, easier to handle, and convenient (Su91)." The Plant Food Association of North Carolina, which includes fertilizer manufacturers and dealers, materials suppliers, NC State University Research and Extension, and NC Department of Agriculture, wrote in April 1990, "Phosphogypsum provides a readily available and economical source of nutrients for our

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Table 5-6. Gypsum sources and application rates for peanuts in North Carolina.

Source	Percent Calcium	Application Rate (lbs/acre) 16-18 in. Band	Broadcast
Bagged (finely ground)	25	600-800	--
420 Granular	25	600-800	1,200-1,600
By-Product Wet Bulk	17	--	1,800-2,300
Granular By-Product	20	750-1,000	1,500-2,000

Eastern North Carolina peanut crop. There are other sources available, but excessively expensive (Yo90)."

5.3 PEANUT FARMING IN VIRGINIA

According to S. Mason Carbaugh, Commissioner of the Commonwealth of Virginia's Department of Agriculture and Consumer Services, and his staff, "an adequate supply of gypsum is available in Virginia to meet the needs of Virginia farmers (Ca90)." Carbaugh investigated prices for substitutes and found a price of $24.30 an acre for gypsum from U.S. Gypsum and $15.75 an acre for gypsum from Materials Byproducts, Inc. Phosphogypsum, available in Virginia from Texasgulf, was comparatively priced at $15.75 an acre. All prices are FOB at a dealer warehouse. The Virginia Farm Bureau Association estimates that banning the use of phosphogypsum would cost southeast Virginia peanut farmers, who currently use phosphogypsum, $20 more an acre for an alternative. The Association estimates that this increased cost would translate into a cost of several million dollars a year for the farmers of the approximately 100,000 acres of peanuts in Virginia (As90).

5.4 AGRICULTURE IN FLORIDA

AGRO Services International, Inc., under a grant sponsored by the Florida Institute of Phosphate Research, researched the use of phosphogypsum as a fertilizer on several Florida crops (AGRO89). As part of this study, AGRO Services completed field trials using various rates and placement of phosphogypsum (holding constant the addition of other fertilizers containing nutrients not in gypsum) in order to determine the yield response of several crops to phosphogypsum. As well as determining yield response for each crop tested, AGRO determined the economic returns due to the use of phosphogypsum on the crops. By assigning a cost to phosphogypsum and its application, assigning a selling price to the tested crops, and by using the percentage yield increases of the experiment, AGRO found that only

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cowpeas present a real risk in obtaining an economic return on investment in phosphogypsum among the crops tested. See Table 5-7 for a summary of the AGRO study. Application of phosphogypsum on the crops, other than cowpeas, is highly likely to result in strong economic returns, because the percentage increases in the last column of Table 5-7 are substantially higher than the break-even levels.

5.5 AGRICULTURE IN IDAHO

Simplot operates a plant in Pocatello, Idaho. In 1988 Simplot sold approximately 40,000 to 50,000 tons of phosphogypsum for use on alfalfa, onion, and potato crops in Idaho. In 1991, Simplot only sold approximately 4,500 tons of phosphogypsum for use on a ranch which produces corn, potatoes, and wheat. Due to the regulatory uncertainty surrounding the use and sale of phosphogypsum, they no longer promote sales (Mc91).

5.6 AGRICULTURE IN CALIFORNIA

According to The Fertilizer Institute, phosphogypsum is used on a variety of crops in California including citrus, almonds, vegetables, and tomatoes. The 1988 sales of phosphogypsum in California were 84,507 tons. The Fertilizer Institute estimates, however, that 1990 demand for gypsum for agricultural use in California is at 500,000-750,000 tons per year (TFI90b). Four Court, Inc., whose 1990 sales of phosphogypsum to California sources were 50,000 tons, questions the use of alternative mined gypsum from Utah. They suggest that mined gypsum from one Utah source contains high levels of uranium and thorium (Se90).

5.7 ROAD BUILDING IN FLORIDA

5.7.1 Availability

In a study considering the use of phosphogypsum for secondary road construction, the University of Miami writes, "Traditional road building materials, such as limerock, shellrock, shell, and clay are in short supply in many parts of Florida. Significant tonnages of aggregates used in road construction are now imported from foreign countries. The U.S. Bureau of Mines has forecasted that Florida will have to import all its aggregate by the year 2000 (UoM89)." The study suggests phosphogypsum as an alternative. According to the Florida Department of Transportation, however, limestone - the primary material used as a roadbase in the state of Florida - is plentiful from local sources throughout the state of Florida with a few exceptions. Natural sand-clay material and natural shellrock are also available in limited supply in some areas (He91). Thus, there appears to be differing opinions on the availability of roadbase materials in Florida, and the need for phosphogypsum in road construction is unclear.

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Table 5-7. Economic returns using phosphogypsum on selected Florida crops.

Crop	Selling Price of Produce (Dollars)	Average Yield of Crop Without Phosphogypsum (pounds)	Cost of Phosphogypsum ($/acre)	Percentage Increase Needed to Break Even		Percentage Increase Found
				Using 1000 lbs/acre	Using 2000 lbs/acre	
Cantaloupe	0.10	36000	90	2.5	5	37
Sweet Corn	0.12	24000	90	3.1	6.2	55
Cow Peas	0.06	[a]	90	12.5	25	20
Bell Peppers	0.25	12000	90	1	2	40
Potatoes	0.08	60000	90	1.9	3.8	22
Tomatoes	0.14	36000	90	1.8	3.6	6
Watermelon	0.05	[a]	90	4.5	9	49

[a] Value missing from the source document.

Source: "Uses of Phosphogypsum Fortified With Other Selected Essential Elements as a Soil Amendment on Low Cation Exchange Soils." Prepared by Agro Service Intl., Inc. under a grant sponsored by the Florida Institute of Phosphate Research, Bartow, Florida, November 1989.

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5.7.2 Cost

The University of Miami in conjunction with the Florida Institute of Phosphate Research constructed one and one-half miles of secondary road (Parrish Road) utilizing phosphogypsum(UoM89). They then compared the costs of building the road to the costs encountered in building two similar roads. The roads used for comparative purposes, Tanner Road and Windy Hill Road, were built in Polk County about the same time as Parrish Road, but were built with clay. The building of Parrish road was broken down into 9 tasks for which economic data (labor, capital, and energy expense) were collected. The tasks included: setting stakes and grading, hauling gypsum, spreading gypsum, boxing out and shaping up, mixing subgrade and gypsum, watering, final blade, compaction, and foreman's work. According to the analysis, the total cost for building Tanner Road and Windy Hill Road were $98,339 per mile and $129,320 per mile, respectively. In comparison, the cost of building Parrish Road was $23,485 per mile. Figure 5-1 breaks these costs down by vehicle, material, and labor costs. The road built with phosphogypsum materials has no material costs as the road was built close to the source of the phosphogypsum and the phosphogypsum was donated to the project. In order for the cost of building Parrish Road to equal the cost of Tanner Road and Windy Hill Road, the amount of phosphogypsum necessary to build one mile of road and the transportation of that amount of material would have to cost $74,854 and $105,835, respectively.

It is possible to estimate the cost of phosphogypsum to construct one mile of roadway using information provided in the BID; however, it is difficult to estimate the transportation costs. Because the transportation cost is a function of the haulage distance, it is possible, however, to estimate the distance phosphogypsum can be transported and not exceed the cost of using conventional materials ($74,854 and $105,835). The following information was provided earlier in this document.

- Roadbed Dimensions (Figure 4-1) - 0.25 m thick x 9.15 m wide x 1613 m long
- Roadbed Material Density (Table 4-5) - 2250 kg/m^3
- Cost of Phosphogypsum (Table 5-3) - $13.00/ton
- Transportation Cost (Table 5-4) - $0.10/ton-mile

Using this information, one mile of roadbed will contain 3690 m^3 of material weighing 9,151 tons. Phosphogypsum is usually mixed in various ratios with soil (clay/sand) in roadbed preparation. The amounts of phosphogypsum required and its cost for three commonly used mixtures are:

Phosphogypsum: Soil Mixture	Amount (tons)	Cost ($)
1:2	3,050	39,650
1:1	4,576	59,488
2:1	6,101	79,313

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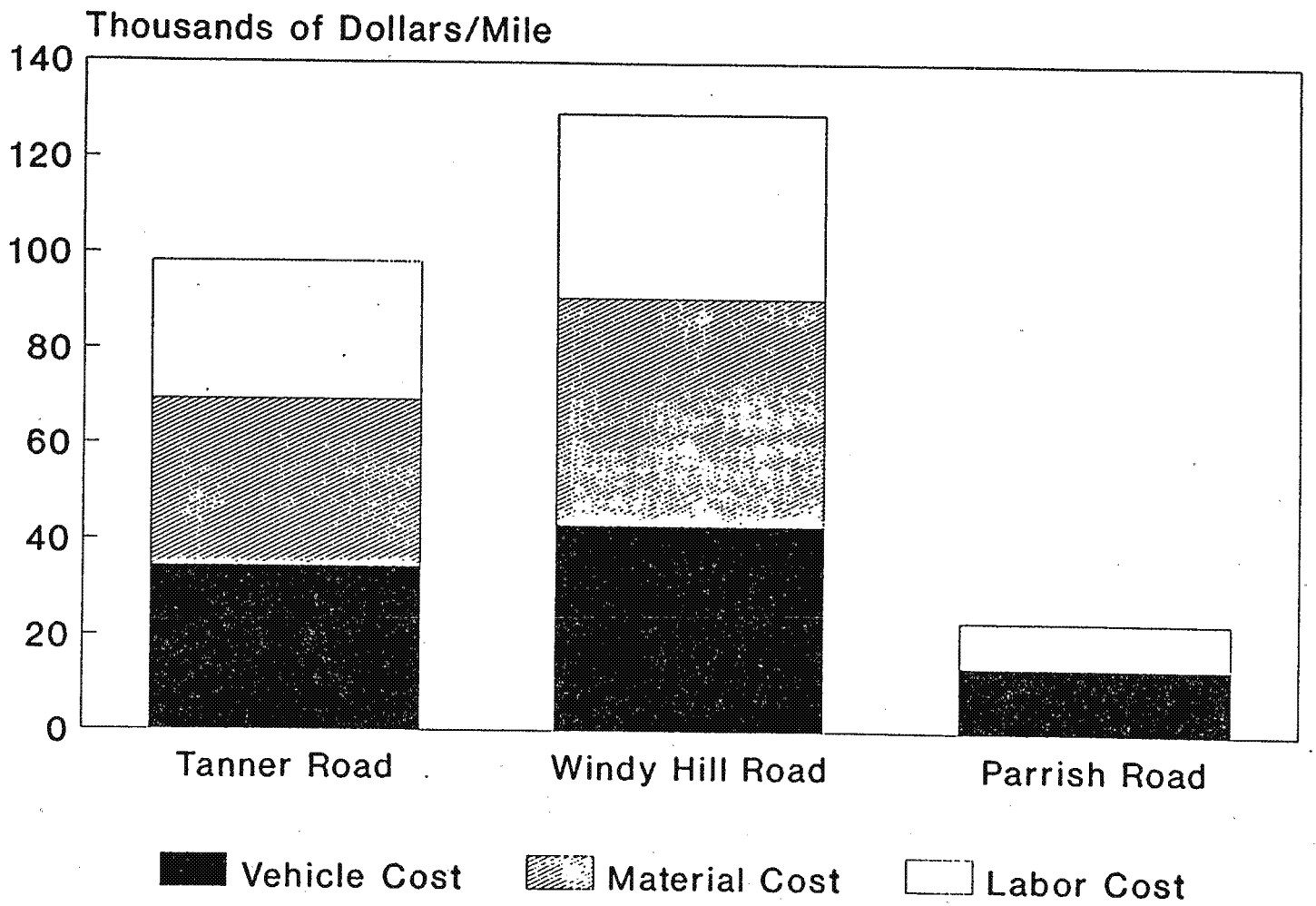
Fig. 5-1. Road building cost comparison-
traditional material vs. phosphogypsum.



Source: UoM89

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Thus, the amount of money for transportation costs not to exceed the cost of Tanner ($74,854) and Windy Hill ($105,835) roads will be:

Phosphogypsum: Soil Mixture	Tanner Road ($)	Windy Hill Road ($)
1:2	35,204	66,185
1:1	15,366	46,347
2:1	-4,459	26,522

The distance phosphogypsum could be shipped and not exceed the cost of using conventional materials is presented in Table 5-8.

Table 5-8. Estimated maximum distances phosphogypsum can be hauled for road use and remain competitive with conventional materials.

Phosphogypsum: Soil Mixture	Tanner Road (miles)[a]	Windy Hill Road(miles)[a]
1:2	115	217
1:1	34	101
2:1	0	43

[a] miles = Trans. dollars available ÷ tons required x $ 0.10/ton-mile.

From this analysis, the economical advantage of using phosphogypsum in roadbed construction is not conclusive, but will depend in great part on the transportation costs. Therefore, the viability of using phosphogypsum in road construction will be dependent upon the location of the phosphogypsum in relation to the road construction site and the availability, cost, and location of competing materials.

5.8 RECLAIMING MINED LAND

5.8.1 Availability

Texasgulf produces phosphogypsum as a by-product at its wet phosphoric acid producing plant in Aurora, North Carolina (Pe91). The company's chemical processing facility is adjacent to their phosphate rock mine. In light of the proximity of the two sites, the company spent time and energy developing a method to mix clay, separated from the mined phosphate rock, and by-product phosphogypsum to reclaim mined land. This process, although economical for Texasgulf, may not be economical for other companies because the mines and the chemical processing plants of the other companies may not be close enough

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together to make the blending process economical, and the clay recovered from the phosphate rock in other locations may not be suitable for this type of process.

5.8.2 Cost

Quantitative figures on the savings Texasgulf achieves by reclaiming mined land were not available. However, obvious savings include the cost of building and maintaining phosphogypsum stacks and clay settling ponds. Additionally, land reclaimed with the phosphogypsum/clay blend is available for use sooner than when it is reclaimed with only clay. Texasgulf estimates that land reclaimed with the phosphogypsum/clay mixture is suitable for revegetation approximately 9 months after reclamation. Alternatively, land reclaimed with only clay may take 20 plus years before it is suitable for revegetation.

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APPENDIX A

PATHRAE PATHWAY EQUATIONS

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APPENDIX A
PATHRAE Pathway Equations

A.1 PROGRAM DESCRIPTION

The PATHRAE methodology models both offsite and onsite pathways through which man can come in contact with the waste. For each of the pathways, the dose from each nuclide is calculated as a function of time. These doses are then summed to give the total dose for the pathway. The dose to the CPG from all pathways is then computed, assuming the entire nuclide inventory is accessible through each pathway.

In this assessment, the PATHRAE code considered eight pathways by which radioactivity may reach humans. These pathways were:

1. Groundwater migration with discharge to a river.
2. Groundwater migration with discharge to a well.
3. Surface erosion of the cover material and subsequent contamination of surface water.
4. Food grown on the site.
5. Direct gamma exposure.
6. Inhalation of radioactive dust on site.
7. Inhalation of radon gas and radon daughters on site.
8. Inhalation of radioactive particulates offsite (dust resuspension).

A.2 PATHWAY EQUATIONS

The equations used to calculate the doses, D, for each of the eight pathways are presented in this section. References are given to aid the reader in understanding the assumptions on which the equations are based and, where appropriate, some discussion is given of the important features of the equations. In general, the equations can be grouped into three components representing the waste form or release rate, the transport pathway, and environmental uptake. For simplicity, the results of the environmental foodchain analysis are represented in the equations by the symbol, U, called the equivalent uptake factor.

A.2.1 Pathway One - Groundwater to a River

Groundwater migration with discharge to a river is calculated from the following equation:

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$$D = \frac{Q\lambda_L f_o U_1 (DF)}{q_w} \qquad \textbf{(A-1)}$$

where

Q	=	inventory of the isotope available in a given year (pCi)
q_w	=	flow rate of the river (m^3/yr)
f_o	=	fraction of inventory arriving at the river from transport through the aquifer
λ_L	=	fraction of each nuclide leached from the inventory in a year (l/yr)
U_1	=	annual equivalent uptake by an individual (m^3/yr)
DF	=	dose conversion factor (mrem/pCi)

The components of the equation are:

Release Rate = $Q\ \lambda_L$
Transport Pathway = f_o
Environmental Uptake = U_1 / q_w (DF)

The term f_o can be calculated for dispersive groundwater transport using two methods. For the first case, a constant fraction leach model is used to obtain a non-dispersion solution, which is modified by the Hung Correction Factor[4] to obtain a dispersion solution form for f_o given by:

$$f_o = 0 \qquad \text{for } t \le t_1 - t_0$$

$$f_o = \frac{v_a F_h}{LR\lambda_L}\left[1-\exp[-\lambda_L(t-(t_1-t_0))]\right] \text{ for } t_1 - t_0 < t < t_1 . \qquad \textbf{(A-2)}$$

$$f_o = \frac{v_a F_h}{LR\lambda_L}\exp\left[-\lambda_L(t-t_1)\right]\left[1-\exp(-\lambda_L t_0)\right] \text{ for } t_1 \le t$$

where

t	=	time (yr)
t_0	=	RL/v_a
t_1	=	$R(L+x_w)/v_a$
R	=	retardation factor = $1 + (\rho/p)k_d$

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k_d = sorption coefficient in the aquifer (m^3/kg)

ρ = aquifer density (kg/m^3)

F_h = correction factor for dispersion

λ_L = length of waste site in direction parallel to aquifer flow (m)

v_a = interstitial horizontal aquifer velocity (m/yr)

x_w = distance of groundwater flow for nearest edge of burial pits to the river (m)

p = aquifer porosity.

The term F_h is strictly applicable to a time integration of the release and is given by:[4]

$$F_h = \exp\left[\frac{(L+0.5x_w)}{2D_a}\left(v_a + 2u - \sqrt{4uv_a + v_a 2}\right)\right] , \qquad \textbf{(A-3)}$$

where

D_a = longitudinal dispersivity (m)

u = $R\lambda D_a$

For dispersive groundwater transport a band release leaching model is used and f_o is given by:[5]

$$f_o = \frac{1}{N}\sum_{j=1}^{N}\left[F_j(t) - F_j(t-1/\lambda_L)\right] \qquad \textbf{(A-4)}$$

where

$F_j(t)$ = $0.5\ U(t)\ [\mathrm{erfc}\ (z-) + \exp(d_j)\ \mathrm{erfc}\ (z+)]$

$U(t)$ = unit step function

$z\pm$ = $\dfrac{\sqrt{d_j}\left[1+t/(Rt_{wj})\right]}{2\sqrt{t/(Rt_{wj})}}$

d_j = distance from sector center to access location, divided by the dispersity

t_{wj} = water travel time from sector center to access location (yr)

N = number of mesh points in numerical integration.

The numerical integration referred to above is a means by which the point source analytical solution for dispersive transport can be extended to approximate an area source. The

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disposal facility of length L is divided into N sectors of equal length. A point source of the appropriate magnitude is placed at the center of each sector. The distance, d_{jh}, is proportional to the distance from the center of sector j to the access location. The point source analytical solutions are then summed over all sectors to approximate an area source.

A.2.2 Pathway Two - Groundwater to a Well

Groundwater migration with discharge to a well is calculated from:

$$D = \frac{Q\lambda_L f_o U_2 (DF)}{q_w} \qquad \textbf{(A-5)}$$

The aquifer dilution water flow rate q_w is given, in this case, by:

$$Q_w = \begin{cases} WLP \text{ for } H_w > L_p \\ WL_p V_a p \text{ for } H_w < L_p \end{cases} \qquad \textbf{(A-6)}$$

where

W	=	width of waste pit perpendicular to aquifer flow (m)
L	=	length of waste pit parallel to aquifer flow (m)
P	=	water percolation rate (m^3/m^2-yr)
L_p	=	length of well casing in aquifer (m)
H_w	=	vertical dimension of contaminated zone in aquifer (m)
v_a	=	horizontal velocity of aquifer (m/yr)
p	=	aquifer porosity
U_2	=	annual equivalent total uptake of well water by an individual (m^3/yr).

The vertical dimension of the contaminated zone, H_w, is related to the other parameters as follows:

$$H_w = \frac{P\,L}{p\,v_a}$$

A well that intercepts the contaminated zone of the aquifer may also draw in uncontaminated water if the length of the well casing, L_p, exceeds H_w. This is why Equation A-6 gives two forms for the dilution rate based on the relative magnitudes of H_w and L_p. In the general use

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of PATHRAE, the factor U_2 differs from U_1 in that contaminated seafood is not included.

In addition to modeling the effects of longitudinal dispersion in the aquifer, the well pathway can account for any transverse dispersion that may occur. This reduces the conservatism when calculating nuclide doses for the well pathway. When modeling transverse dispersion, the term f_o in Equation 2-5 is modified by an additional multiplicative term, f_t, given by:

$$F_t = \frac{1}{2} \text{ erf } \frac{(y_w + W/2)R}{2\sqrt{D_y\, t}} - \frac{1}{2} \text{ erf } \frac{(Y_w - W/2)R}{2\sqrt{D_y\, t}} \qquad \textbf{(A-7)}$$

where

y_w = distance to well from center of water area in the direction perpendicular to the aquifer flow (m)

D_y = transverse dispersion coefficient (m^2/yr).

For the limiting case in which D_y goes to zero, f_t, becomes equal to one. Therefore, the effects of transverse dispersion can be ignored by choosing D_y equal to zero.

The groundwater pathways to the (river and the well) can also accommodate transport in the vertical unsaturated zone between the waste and the aquifer. This is accomplished in the same manner as in the PRESTO codes.[2,4] The vertical water velocity and retardation are given by:

$$V = P/(pS)$$

$$R = 1 + \frac{\rho}{p * s} k_d \qquad \textbf{(A-8)}$$

where

S = fraction of saturation.

The term S can either be input or calculated from the expression:

$$S = S_r + (1 - S_r) \left[\frac{P}{K_h} \right]^{SNO} \qquad \textbf{(A-9)}$$

where

S_r = residual saturation

SNO = soil index

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K_h = vertical zone saturated hydraulic conductivity (m/yr).

A.2.3 Pathway Three - Erosion and Transport to a River

The dose for sheet erosion of cover material and waste and its subsequent deposition in a nearby river is given by:

$$D = \frac{Q f_e f_{dil} U_1 (DF)}{q_w} \qquad \textbf{(A-10)}$$

where

f_{dil} = fraction of solids entering river that originated in waste trenches (calculated internally in the code)

f_e = fraction of waste eroded each year

q_w = river flow rate (m^3/yr).

The parameter f_e is calculated from the surface erosion rate, E_r, which is an input variable, according to the relation $f_e = E_r/t_w$, where t_w is the waste thickness (m) and E_r is expressed in m/yr.

A.2.4 Pathway Four - Food Grown Onsite

The equation for D for food grown over the disposal site is:

$$D = \frac{Q f_d f_g (DF) U_3}{V \quad s} \qquad \textbf{(A-11)}$$

where

V = volume of waste (m^3)

ρ_s = soil density (kg/m^3)

f_d = dilution factor representing the dilution of waste in the soil

f_g = fraction of individual's diet consisting of food grown over the disposal site

U_3 = total equivalent uptake factor for food (kg/yr).

Equation A-11 assumes that at some future time a reclaimer moves onto the waste disposal site and builds a house. By excavating a basement for the house and by drilling a well on the property, some of the waste material is brought to the surface and is mixed with the

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surface soil to some depth (t_g). Using these assumptions, the factor f_d representing the dilution of waste in the surface soil is given by:

$$f_d = f_m \left[\frac{t_m - t_c}{t_g \left(\frac{A_l}{A_h} - 1 \right)} + \frac{t_w}{t_g \left(\frac{A_l}{A_w} - 1 \right)} \right] \qquad \textbf{(A-12)}$$

where

t_w = thickness of the waste (m)

f_m = dilution of waste in the trench before reclaimer activities occur

t_c = thickness of cover (m)

t_m = depth of maximum mechanical disturbance (m)

t_g = depth to which contaminants are mixed with surface soil (m)

A_l = lot area (m^2)

A_h = house area (m^2)

A_w = cross sectional area of wells drilled (m^2).

The first term in the brackets of Equation A-12 is the component due to the excavation of a basement. The second term is the well drilling component. A complete derivation of Equation A-12 is given in Reference 6.

A.2.5 Pathway Five - Direct Gamma

The dose from direct gamma exposure to an intruder is calculated from:

$$D = \frac{Q}{A\mu_w t_w} B(\mu_c t_c) \left[1 + \frac{3\sqrt{\pi}}{4E_\gamma} - B(\mu_{wt_w}) \exp(-\mu_{wt_w}) \right] f_{exp} \, (8760)(DFG) \qquad \textbf{(A-13)}$$

where

$B(\mu t)$ = $1 + (\mu t)^{1.5}/e_\gamma$

μ_w = gamma attenuation constant of the waste (1/m)

μ_c = gamma attenuation constant of the cover (1/m)

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t_w = thickness of the waste (m)

t_c = thickness of the cover (m)

$f_{(exp)}$ = fraction of the year the individual is exposed

A = plane area of the waste, the waste is assumed to be a circular horizontal plane with the exposed individual standing at the center (m^2)

E_γ = weighted average gamma energy emitted by nuclide (MeV)

DFG = infinite ground plane dose conversion factor (mrem/hr per pCi/m^2).

The function, B, in Equation A-13 is the gamma buildup factor which is used to account for the effects of gamma-ray scattering in the waste and in the cover. It is an empirical relation based on gamma scattering data at energies from 0.25 MeV to 1.0 MeV.[7]

The term in brackets in Equation A-13 accounts for self-shielding and buildup in the waste.

The weighted average gamma energy is computed by taking the average of all gamma energies emitted by a particular nuclide, each energy being weighted by its probability of occurrence.

There are three alternatives available when calculating direct gamma doses using PATHRAE. The first alternative allows the calculation of the gamma dose from the undisturbed buried waste. The second alternative assumes that plant roots penetrate the waste and transport some nuclides to the surface. Each year the plants die and deposit their absorbed nuclides on the ground surface, so there is continual transport of nuclides and deposition on the ground surface. The gamma dose is calculated from the nuclides deposited on the surface, as well as the nuclides remaining in the original burial trenches. The third alternative assumes that a reclaimer builds a house and digs a well on the site, as is described under Pathway Five. This brings some of the waste material to the surface where it is mixed with the existing soil. The gamma dose is calculated from the waste on the surface and from the waste that remains underground.

The three options in Pathway Five are selected by the value of the PATHRAE variable IGAMMA which can have the value 0, 1, or 2.

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A.2.6 Pathway Six - Onsite Dust Inhalation

The dose, D, for the inhalation of resuspended dust by an inadvertent intruder is given by:

$$D = \frac{Q f_d \rho_d U_i f_{exp} (DF)}{V \rho_w} \qquad \textbf{(A-14)}$$

where

ρ_w = waste density (kg/m^3)

ρ_d = dust loading in the air breathed (kg/m^3)

f_{exp} = fraction of the year the individual is exposed to dust

U_i = volume of air breathed in a year (m^3/yr)

V = total volume of waste (m^3)

f_d = dilution factor representing the dilution of waste in the soil.

The assumptions for this pathway are similar to those for Pathway Four. That is, a reclaimer builds a house and drills a well over the waste site. The dose arises as a result of inhalation of contaminated dust during the excavation of the house's basement and the drilling of the well. As in Pathway Four, the dilution factor, f_d, is calculated using Equation A-12.

A.2.7 Pathway Seven - Inhalation of Radon in Structures

The dose from inhalation of radon and radon daughters in a structure built over the waste is calculated from:

$$D = \frac{Q}{h\lambda_r VF} E\sqrt{\lambda D_w}\, \tanh(100 b_w t_w) \exp(-100 b_1 t_1 - b_2 t_2)\, U_i (df) \qquad \textbf{(A-15)}$$

where

Q = inventory of Ra-226 (pCi)

E = fraction of radon which can emanate upward from the waste

h = height of rooms in structure built over the waste (cm)

r = air ventilation rate of the structure (air changes/sec)

V = volume of waste (m^3)

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λ = decay constant of radon (1/sec)

t_w = waste thickness (m)

t_1 = thickness of earthen cover (m)

t_2 = thickness of concrete floor in reclaimer house (cm)

D_w = radon diffusion coefficient of the waste (cm^2/sec)

D_1 = radon diffusion coefficient of the cover (cm^2/sec)

D_2 = radon diffusion coefficient of concrete floor (cm^2/sec)

b_i = $\sqrt{\lambda/D_i}$ (i = w, 1, 2)

$$F = \frac{1}{2}\left[1 + \sqrt{a_w/a_c}\ \tanh(b_w t_w)\right] + \frac{1}{2}\left[1 - \sqrt{a_w/a_c}\ \tanh(b_w t_w)\right] \exp(-2(100\ b_1 t_1 + b_2 t_2))$$

a_i = $p_i^2\ D_i\left[1 - (1-k)m_i\right]^2$

m = $0.01\ M\rho/p$

M = moisture content (dry weight percent)

k = 0.26 pCi/m^3 in water per pCi/m^3 in air

p = porosity

U_i = total volume of air breathed in a year (m^3/yr).

A.2.8 Pathway Eight - Atmospheric Transport of Contaminants

The dose from the inhalation of airborne contaminants from dust resuspension (also valid for incinerator or trench fire) is given by:

$$D = \frac{Q}{V}\ r\ f_f\ f_v \left[\frac{X}{Q'}\right] U_i\ (df) \qquad \textbf{(A-16)}$$

where

r = dust resuspension rate or burn rate of incinerator or trench fire (m^3 waste/sec)

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f_f = deposition velocity for dust resuspension (m/sec) or fraction of the year the burning occurs for incinerator and trench fire

f_v = nuclide-specific volatility factor for incineration or trench fire (fraction of nuclide released to atmosphere)

X = downwind atmospheric concentration (pCi/m^3)

Q′ = atmosphere source release rate (pCi/sec).

PATHRAE uses Gaussian plume[9] expressions for X/Q′:

$$\frac{X}{Q'} = \sqrt{\frac{2}{\pi}} \frac{f_w}{\sigma_z u} \frac{n}{2\pi x} \exp\left(-h^2/2\sigma_z^2\right) \qquad \textbf{(A-17)}$$

where

f_w = fraction of time wind blows in direction of interest

σ_w = standard deviation of plume concentration in vertical direction (m)

u = average wind speed (m/sec)

n = number of sectors or wind directions (usually 16)

x = distance from source to receptor (m)

h = effective release height including momentum and thermal plume rise effects (m).

Plume depletion effects from deposition are represented by a reduced source release rate calculated internally to the code.[9]

The actual release height is modified to account for momentum and thermal plume rise effects by the following equations:[9]

$$h = h_s + \frac{1.5\ v_s\ d_s}{u} + \frac{1.6(3.7E{-}5\ x^2\ Q_H)^{0.333}}{u} \qquad \textbf{(A-18)}$$

where

h_s = actual release height (m)

v_s = stack gas velocity (m/sec)

d_s = stack inside diameter (m)

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Q_H = heat emission rate from stack (cal/sec).

Equation A-18 is valid as long as the distance to the receptor location is less than ten times the stack height. For greater distances the receptor distance, x, is replaced with 10 h_s.

If some parameters are unknown or poorly characterized, a default option, based on the location of the maximum plume concentration, is used. In this case:

$$\frac{X}{Q'} = \frac{2}{\pi h^2 e u} \qquad \textbf{(A-19)}$$

where

e = Euler's number (2.71828).

Equations A-17 and A-19 are from Reference 10 and are expressions for point sources. For the trench fire scenario it is assumed that the fire involves a relatively small amount of waste (for example, the amount received by the facility in one day). For an incinerator the only source is a single incinerator stack. Since the extent of the source is small in these cases, the use of the point source expression is justified.

If an area source is desired it can be represented by the virtual point source approximation, where x is replaced by x′, given by[1]

$$x' = x + 1.5137\ y$$

where

y = width of the facility (m)

The σ_z in Equation A-17 is calculated in PATHRAE using Briggs' approximations.[9] This necessitates specifying one of the six Pasquill atmospheric stability classes. If no stability class is specified in the input data set, the moderately stable Class D is used. The stability class should be chosen to represent an annual average stability. The wind speed, u, is the annual average wind speed in the direction from source to receptor.

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APPENDIX B

RA-226 SOIL CONCENTRATION CALCULATIONS

ED_005285_00000283-00114

APPENDIX B
Ra-226 Soil Concentration Calculations

Radium-226 soil concentrations, resulting from periodic applications of phosphogypsum, can be calculated by solving a standard mass balance equation:

$$\frac{dC}{dt} = K - kC \qquad \textbf{(B-1)}$$

The solution to equation B-1 is obtained through standard differential equation solution techniques, and is found to be:

$$C = \frac{K}{k}(1 - e^{-kt}) \qquad \textbf{(B-2)}$$

Using the boundary condition of C=0 at t=0, the arbitrary constants can be solved for. The resulting solution then becomes:

$$Cs = \frac{k_i\, C_{pG}}{W} * \frac{1}{k_2 + k_3 + k_4 + k_5)} * (1 - e^{-(k_2 + k_3 + k_4 + k_5)t}) \qquad \textbf{(B-3)}$$

where

Cs	=	Ra-226 concentration in soil (pCi/g)
C_{pG}	=	Ra-226 concentration in phosphogypsum (pCi/g)
k_i	=	application rate of phosphogypsum (g/yr)
W	=	mass of soil (g)
k_2	=	Ra-226 decay rate (4.3×10^{-4} yr^{-1})
k_3	=	rate loss of Ra-226 due to uptake by plants (2.6×10^{-6} yr^{-1})
k_4	=	rate loss of Ra-226 by leaching (2.8×10^{-5} yr^{-1})
k_5	=	rate loss of Ra-226 by wind erosion (8.9×10^{-4} yr^{-1})

Using the data in the table presented below, the Ra-226 soil concentration can be calculated after 100 years of biennial phosphogypsum application.

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Table B-1. Ra-226 soil concentration calculation parameters.

Parameter	Scenario 1 & 2	Scenario 3 & 4	Scenario 5 & 6
k_2 (yr^{-1})	4.3E-04	4.3E-04	4.3E-04
k_3 (yr^{-1})	2.6E-06	2.6E-06	2.6E-06
k_4 (yr^{-1})	2.8E-05	2.8E-05	2.8E-05
k_5 (yr^{-1})	8.9E-04	8.9E-04	8.9E-04
k_i (g/yr)	4.6E+07	1.0E+09	1.1E+09
t (yrs)	100	100	100
W (g)	1.9E+11	2.8E+12	1.0E+12
CpL (pCi/g)	30	30	30

A summary of the Ra-226 soil concentrations calculated for scenarios 1-6 is presented in Table B-2.

Table B-2. Ra-226 soil concentrations.

Scenario	Ra-226 Concentration (pCi/g)
1 & 2 (Agriculture: Average Case	0.69
3 & 4 (Agriculture: Maximum Case)	1.02
5 & 6 (Soil Amendment)	3.12

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APPENDIX C

RISK ASSESSMENT FOR THE INGESTION OF TREATED SOIL

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APPENDIX C
Risk Assessment for the Ingestion of Treated Soil

The risks that result from the direct ingestion of treated soil has been estimated using the following information:

1. Exhibit 6-14 of the Superfund Risk Assessment Guidance handbook
   a. Ingestion Rate
      - 200 mg/d 1-6 yrs of age
      - 100 mg/d 6-70 yrs of age
      - 365 days/yr

   b. Exposure Periods
      - 70 yrs - lifetime
      - 30 yrs - 90 percentile residency
      - 9 yrs - national average residency

   c. Total Uptake

9 Year Exposure

$$(200\ mg/d)(365\ d/y)(6\ y)+(100\ mg/d)(365\ d/y)(3\ y)= x\ mg$$
$$438{,}000\ mg + 109{,}500\ mg = x\ mg$$
$$547{,}500\ mg = x\ mg$$
$$547.5\ g$$

30 Year Exposure

$$(200\ mg/d)(365\ d/y)(6\ y)+(100\ mg/d)(365\ d/y)(24\ y)= x\ mg$$
$$438{,}000\ mg + 876{,}000\ mg = x\ mg$$
$$1{,}314{,}000\ mg = x\ mg$$
$$1{,}314\ g$$

70 Year Exposure

$$(200\ mg/d)(365\ d/y)(6\ y)+(100\ mg/d)(365\ d/y)(64\ y)= x\ mg$$
$$438{,}000\ mg + 2{,}336{,}000\ mg = x\ mg$$
$$2{,}774{,}000\ mg = x\ mg$$
$$2{,}774\ g$$

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Table C.1. Scenario 13 - Based on 10 pCi Ra-226/g of phosphogypsum applied at the rate of 664 kg/acre biennially for 100 years.

Nuclide	Relative[1] Concentration (pCi/g soil)	RF[2] (Risk/uCi)	70 YR Risk	30 YR Risk	9 YR Risk
Ra-226	0.69	9.4 E-5	1.8 E-7	8.5 E-8	3.6 E-8
Po-210	0.66	1.4 E-4	2.6 E-7	1.2 E-7	5.1 E-8
Pb-210	0.89	5.5 E-4	1.4 E-6	6.4 E-7	2.7 E-7
Th-228	0.09	1.3 E-5	3.3 E-9	1.5 E-9	6.4E-10
Ra-228	0.09	7.0 E-5	1.8 E-8	8.3 E-9	3.5 E-9
Th-230	0.12	2.3 E-5	7.7 E-9	3.6 E-9	1.5 E-9
Th-232	0.08	2.1 E-5	4.7 E-9	2.2 E-9	9.2E-10
U-234	0.08	7.5 E-5	1.7 E-8	7.9 E-9	3.3 E-9
U-235	0.003	7.3 E-5	6.1E-10	2.9E-10	1.2 E-10
U-238	0.07	7.4 E-5	1.4 E-8	6.8 E-9	2.8 E-9
TOTAL RISK			1.9 E-6	8.8 E-7	3.7 E-7

1 Soil concentrations after 100 years of application taking into consideration removal mechanisms.

2 Risk factors from Table A-5 of EPA89b.

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Table C.2. Scenario 14 - Based on 26 pCi Ra-226/g of phosphogypsum applied at the rate of 8,000 Kg/acre initial application followed by biennial applications of 4,000 Kg/acre for 100 years.

Nuclide	Relative[1] Concentration (pCi/g soil)	RF[2] (Risk/uCi)	70 YR Risk	30 YR Risk	9 YR Risk
Ra-226	2.74	9.4 E-5	7.1 E-7	3.4 E-7	1.4 E-7
Po-210	2.64	1.4 E-4	1.0 E-6	4.8 E-7	2.0 E-7
Pb-210	3.55	5.5 E-4	5.4 E-6	2.6 E-6	1.1 E-6
Th-228	0.34	1.3 E-5	1.2 E-8	5.8 E-9	2.4 E-9
Ra-228	0.34	7.0 E-5	6.6 E-8	3.1 E-8	1.3 E-8
Th-230	0.47	2.3 E-5	3.0 E-8	1.4 E-8	6.0 E-9
Th-232	0.31	2.1 E-5	1.8 E-8	8.8 E-9	3.6 E-9
U-234	0.30	7.5 E-5	6.3 E-8	3.0 E-8	1.2 E-8
U-235	0.013	7.3 E-5	2.6 E-9	1.2 E-9	5.0 E-10
U-238	0.28	7.4 E-5	5.7 E-8	2.7 E-8	1.1 E-8
TOTAL RISK			7.4 E-6	3.5 E-6	1.5 E-6

1 Soil concentrations after 100 years of application taking into consideration removal mechanisms.

2 Risk factors from Table A-5 of EPA89b.

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

DEC 2 2 2004

OFFICE OF
AIR AND RADIATION

Mr. G. Michael Lloyd, Jr.
Research Director Chemical Processing
Florida Institute of Phosphate Research
1855 West Main Street
Bartow, FL 33830-7718

Dear Mr. Lloyd:

This letter is official notice that the Environmental Protection Agency (EPA) conditionally approves the petition the Florida Institute of Phosphate Research (FIPR) filed requesting an alternate use of phosphogypsum under 40 CFR 61.206. The petition, Application for Research Use of Phosphogypsum as Cover Material in a Landfill Test Cell, submitted December 9, 2003, along with the supplemental information you provided on July 23, 2004 has been used as the basis for this finding.

Our rationale for conditionally approving your request was based on the following three elements:

- Your demonstration that the alternative use is at least as protective as placement of phosphogypsum in a stack or mine, consistent with the regulations.

- The proposed monitoring scheme, covering both radiological and non-radiological parameters, is presented with sufficient detail to demonstrate the project does not adversely affect the environment. Monitoring shall include gases, leachate, and the analysis of ground water as described in the petition and attached conditions.

- The protocols suggested in your petition to analyze the efficacy of the testing procedures lie within generally accepted methodologies for such research.

Consistent with 40 CFR 61.206(e), we have decided to impose additional terms governing the distribution or use of the phosphogypsum as described in your petition as amended. Please see the attached conditional approval for further information about the conditions placed on this approval, and the addresses of the public libraries where you will need to place the petition, this letter, and the attached conditional approval.

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We will publish a notice of our pending approval in the local newspapers near the site and stack (*Brevard Florida Today* and *The Lakeland Ledger*) informing the public of our pending approval, the location of the libraries where the petition is available for public review, and notice that we will approve the petition after the 30 day comment period unless significant adverse comments are received. We will also directly notify other stakeholders of our pending approval.

We will make all comments we receive available to the public. Upon receipt of public comments, we will review them for their significance and determine if they contain information that would alter this decision for approval. Some examples would be: significant concerns for human health or environmental impacts that were not previously considered in the risk analysis; some other reason to reconsider our decision to approve; or the potential to revise the finding that the alternative use is at least as protective as leaving the phosphogypsum in the stack. If we determine that there are significant comment(s), and believe that this alternative use should not proceed, we will advise you and give you an opportunity to amend your analysis or proposed use, or take other steps to address the public concerns.

We look forward to a continued working relationship with you on this petition, and other future petitions your Institute may develop that protectively use phosphogypsum. Please contact Reid Rosnick of my staff at 202-343-9563 if you have any questions.

Sincerely,

Jeffrey R. Holmstead
Assistant Administrator

Attachment

cc: Hon. Adam Putnam
Hon. Katherine Harris
Hon. Leo Longworth, Mayor, Bartow, FL
Hon. Michael Blake, Mayor, Cocoa, FL
Elizabeth Cotsworth
Elliott Zenick, OGC
Van Shrieves, Region 4
William Kutash
William Pascetti
Euripides Rodriguez

bcc: Bonnie Gitlin
Adam Klinger
Reid Rosnick
Catherine Sulzer, OCIR
Michael Gonsalves, FL DEP
Jeff Steadham, Tampa Tribune

4. The Applicant shall analyze the leachate and gas generated from the test cell as

Proposed Conditional Approval
Alternative Use of Phosphogypsum

The United States Environmental Protection Agency (EPA) is proposing to grant conditional approval to the petition the Florida Institute of Phosphate Research (FIPR, Applicant) filed requesting an alternate use of phosphogypsum under 40 CFR 61.206. The petition is comprised of the following: Application for Research Use of Phosphogypsum as Cover Material in a Landfill Test Cell, submitted December 9, 2003, along with the supplemental information provided on July 23, 2004. After carefully reviewing all of the information submitted, EPA has decided to grant the alternative use of phosphogypsum, contingent upon the following conditions:

1. The proposed conditional approval is valid for this specific petition as submitted and amended by the Applicant, and approved by EPA. Any other requests for alternative uses of phosphogypsum shall be specific to that particular instance.
2. The Applicant, upon receipt of this proposed conditional approval, shall submit the complete petition as described above, and this approval to the following public libraries:
   - Bartow Public Library
     2150 S. Broadway Avenue
     Bartow, FL 33830, and
   - Central Brevard Public Library and Reference Center
     308 Forrest Avenue
     Cocoa, FL 32922

   The thirty day comment period shall begin when the notices for comment are placed by EPA in the following newspapers:
   - *The Lakeland Ledger*
   - *Brevard Florida Today*
3. The Applicant shall meet all of the applicable requirements of 40 CFR 61.200-210, Subpart R. This approval does not supercede the requirements of any other federal or State of Florida regulation.
4. The Applicant shall analyze the leachate and gas generated from the test cell as outlined in the petition (weekly), and shall electronically submit those results to EPA and the Florida Department of Environmental Protection (DEP) semi-annually. Requests for changing the sampling interval for gas and leachate (or for any procedures outlined in the petition) shall be submitted to EPA, and EPA shall either approve or deny the request.
5. The Applicant shall electronically submit to EPA and the Florida DEP within sixty days of receipt of results the semi-annual ground-water analyses performed by the Brevard County Landfill.
6. At the end of the test phase, the Applicant shall submit to EPA and the Florida DEP a complete final report on the test, including conclusions on the efficacy of the use of phosphogypsum in the test.

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Comparison of Coal Combustion Products to Other Common Materials

Chemical Characteristics

Comparison of Coal Combustion Products to Other Common Materials

Chemical Characteristics

1020556

Final Report, September 2010

EPRI Project Manager
K. Ladwig

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REPORT SUMMARY

The chemical characteristics of coal combustion products (CCPs) are often discussed with reference to geologic materials and other industrial by-products; however, there are no systematic comparisons of these materials in the literature. This report compares the ranges in chemical characteristics of fly ash, bottom ash, and flue gas desulfurization (FGD) gypsum to the ranges observed for soil and rock, as well as other common products and by-products.

Background

At scientific conferences and in trade journals and the popular media, CCPs are sometimes described as being similar in composition to soils; at other times they are referred to as toxic or hazardous substances. Often, general statements are made with little or no data given to support these characterizations. Such statements can be misleading and have led to confusion, especially among the general public. To provide a more technical basis for characterizing CCP composition, this project collected representative data from the literature and used it as a basis for comparing a number of common materials to each of the types of coal combustion products.

Objectives

- To collect representative data on the chemical characteristics of soil, rock, and selected products and by-products from the literature
- To present a graphic comparison of these data to data on the chemical characteristics of fly ash, bottom ash, and FGD gypsum

Approach

The basic approach was to compare CCPs to other materials using bar charts showing concentration ranges for a number of major and trace constituents. Major element composition of coal fly ash, bottom ash, and FGD gypsum was compared to that of soils and rocks. Trace element concentrations for the CCPs were compared to those for soils, rocks, fertilizers, metal slags, spent foundry sands, and biosolids. Where data were readily available, ranges in leachate concentrations were also compared. Trace element concentrations and leachate concentrations were also compared to regulatory levels. CCP data were derived largely from the Electric Power Research Institute (EPRI) databases containing total composition and leaching characteristics. For the other materials, a literature review was performed to identify data that are current and representative.

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Results

- The major chemical composition of both bottom ash and fly ash is similar to that of siliceous rocks, particularly shale. Oxides of silicon, aluminum, iron, and calcium make up more than 90% of most siliceous rocks, soils, fly ash, and bottom ash. Trace elements account for less than 1% of all these materials.
- FGD gypsum is very similar chemically to mined rock gypsum. Both are composed primarily of hydrated calcium sulfate. FGD gypsum is typically more than 90%–95% pure, whereas the purity of mined gypsum is more variable.
- Trace element ranges for fly ash were typically higher than the ranges for soil, rock, and foundry sand and were comparable to or sometimes higher than the ranges for fertilizer, metal slags, and biosolids.
- Trace element ranges for bottom ash were typically higher than the ranges for soil and foundry sands; comparable to or sometimes higher than the ranges for rocks, fertilizers, and biosolids; and comparable to the ranges for metal slags.
- With a few exceptions, trace element ranges for FGD gypsum were generally comparable to or lower than the ranges for rocks and fertilizers and lower than the ranges for soils, metal slags, foundry sands, and biosolids.
- Concentration ranges of trace constituents in fly ash, bottom ash, and FGD gypsum typically fall below the Environmental Protection Agency (EPA) residential soil screening levels and industrial soil screening levels for ingestion and dermal exposure, with the exception of arsenic. Many other materials, including uncontaminated soils and other beneficially used materials, also commonly exceed these screening levels for arsenic.
- CCPs did not exceed any hazardous waste limits in the toxicity characteristic leaching procedure test data from EPRI studies that included 64 samples from 50 power plant sites.

EPRI Perspective

EPRI research on CCPs over the last 30 years has included a variety of laboratory and field studies; one result of this research is a comprehensive database of CCP characteristics under a variety of environmental conditions. Topics of current research include changes in CCP characteristics resulting from new air emissions controls and methods to reduce leaching of trace constituents in certain construction applications.

Keywords

Flue gas desulfurization gypsum
Foundry sand
Fly ash
Metal slag
Rocks
Soils

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1
INTRODUCTION

Background

Coal combustion products (CCPs)—fly ash, bottom ash, slag, and flue gas desulfurization (FGD) solids—are produced when coal, a sedimentary rock, is burned to generate electricity. Coal, the parent material of fly ash and bottom ash, contains primarily organic matter along with smaller amounts of inorganic rock fragments and mineral matter. When the organic matter is released from coal during combustion, most of the inorganic matter either drops to the bottom of the boiler as bottom ash, or is captured from the flue gas as fly ash. As a result, fly ash and bottom ash are composed of the same elements as rocks and soils, although the trace elements are enriched relative to the parent coal.

FGD solids are produced when an alkaline material, usually limestone or lime, is added to the flue gas to react with sulfur dioxide. The reaction produces calcium-sulfur compounds that are then removed from the flue gas. The most common FGD process is one using limestone and forced oxidation to form FGD gypsum ($CaSO_4 \cdot 2H_2O$). FGD gypsum and mined gypsum are chemically similar and find many of the same uses in products. Both also contain some trace constituents.

This report compares the chemical characteristics of coal combustion products to the chemical characteristics of natural materials and selected manufacturing by-products. Chemical characteristics of coal fly ash, bottom ash, and FGD gypsum are compared to those of materials such as soils, rocks, fertilizers, metal slags, biosolids, and spent foundry sands. Materials were chosen on the basis that they were either naturally occurring or were beneficially reused by-products or products. The basic approach was to provide a graphic comparison of the trace element concentration ranges of CCPs to those of other materials. Data used to produce the graphics are also provided.

Report Organization

Each section of this report compares CCPs with a particular solid material. Section 2 describes the source of all CCP data that are used throughout the report. Sections 3 and 4 present data for rocks and soils, respectively. Extended discussion is provided regarding selection of a data source for soil concentrations. Section 5 compares trace constituents in CCPs and fertilizers. Sections 6, 7, and 8 compare trace constituents in CCPs and beneficially used materials—metal slags, biosolids, and spent foundry sands, respectively. Section 9 presents chemical

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characteristics of CCPs in the context of regulatory thresholds such as EPA soil screening levels and Toxicity Characteristic Leaching Procedure analyses. Section 10 concludes the report with a brief summary of important findings.

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2
DATA AND METHODS

Summaries of all concentrations used for comparison in this study are listed in Tables 2-1 and 2-2. Data sources for materials other than CCPs are discussed in sections of the report where data are compared.

Coal combustion product data were obtained primarily from the CP-Info database (EPRI, 2009a). Where data were not available in CP-Info, data were obtained from the EPRI PISCES database (EPRI, 2009b). The CP-Info and PISCES databases contain results generated during 30 years of EPRI research and represent a broad range of CCP materials. Reports used to compile data for CP-Info include:

- EPRI, 1986. ***Mobilization and Attenuation of Trace Elements in an Artificially Weathered Fly Ash.*** EPRI, Palo Alto, CA. EA-4747.
- EPRI, 1987. ***Matrix Isolation Spectroscopy and the Stability of Polycyclic Aromatics in Coal Ash: Final Report.*** EPRI, Palo Alto, CA. EA-5148.
- EPRI, 1987. ***Chemical Characterization of Fossil Fuel Combustion Wastes.*** EPRI, Palo Alto, CA. EA-5321.
- EPRI, 1994. ***A Field and Laboratory Study of Solute Release from Sluiced Fly Ash.*** EPRI, Palo Alto, CA. TR-104585.
- EPRI, 1995. ***Effects of Flue Gas Desulfurization (FGD) System Additives on Solid By-Products.*** EPRI, Palo Alto, CA. TR-102367.
- EPRI, 1996. ***Mixtures of a Coal Combustion By-Product and Composted Yard Wastes for Use as Soil Substitutes and Amendments.*** EPRI, Palo Alto, CA. TR-106682.
- EPRI, 1999. ***Utilization of Coal Combustion By-Products in Agriculture and Land Reclamation.*** EPRI, Palo Alto, CA. TR-112746.
- EPRI, 2002. ***Mercury Releases from Coal Fly Ash.*** EPRI, Palo Alto, CA. 1005259.
- Gustin, M. and Ladwig, K., 2004. ***An assessment of the significance of mercury release from coal ash.*** Journal of the Air and Waste Management Association 54(320-330).
- EPRI, in preparation. ***FGD Gypsum Characterization Data.*** EPRI, Palo Alto, CA. Scheduled for publication in 2010.

In many studies, multiple CCP sample analyses originate from a single power plant. This created the potential for biasing the dataset, overweighting results produced from a single plant. In the current investigation, results known to originate from a single plant were averaged to produce a single concentration for that plant site. This concentration was then used in

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subsequent statistical calculations. Although this approach limited the number of data points available for analysis, it achieved a more representative sampling across the electric utility industry without biasing results from one plant.

In this report, the following statistical values are used: median, minimum, maximum, 10th percentile, and 90th percentile. Median values are also known as the 50th percentile, or data point at which half the values fall below and half fall above. Minima and maxima are the smallest and largest data points in the dataset, respectively. Where possible, the 10th and 90th percentile values were used as better representations of data ranges, due to the possibility of outlier data. In some cases, percentile values were not calculated, due either to lack of data or to the high potential for bias in the dataset. In the case of metal slags, there were not enough data reported to calculate percentages. In the case of fertilizers, the very large variability in reported fertilizer type and manufacturers made percentile calculations less reliable than a comparison of minima and maxima.

In many cases, some or all statistical values were less than method detection limits. In these cases, the detection limit was substituted as the value for that statistic. Ranges are non-existent for the cases where all values are less than detection limits, and are represented graphically as single points or bars. In the case of cadmium in fly ash, the dataset contained a few detection limits higher than most of the detected values. In this case, all non-detects higher than the median of detects were excluded.

Data are presented using bars representing the concentration range of the CCP plotted against the concentration range of the material being compared. Graphically, using a log scale allows plotting of multiple elements on one graph, maintaining the ability to visually compare concentration ranges. The bars are bounded by 10th and 90th percentiles, or by minima and maxima. Elements are then qualitatively grouped into one of seven categories, depending upon how the CCP concentration range compares graphically to the selected material.

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Table 2-1
Statistical summary of the concentrations of various elements in coal combustion products (all concentrations in mg/kg)

Fly Ash		As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Sb	Be
	# Sites	59	39	28	59	58	19	59	36	38	229
	Max	1385	10850	17	651	2120	1.3	47	13	131	826
	90th Perc.	261	5064	6.2	298	143	0.5146	18	7.6	16	26
	50th Perc.	71	923	1.07	133	49	0.1075	11	<4.9	<7.2	10.6
	10th Perc.	22	381	0.36	27	21	0.0104	1.8	<4.9	<7.2	2.2
	Min	8.1	239	<0.11	11	13	<0.0025	<1.4	<4.9	<7.2	<0.4
		B	Co	Cu	Mn	Ni	Tl	V	Zn	Fe	Mo
	# Sites	26	3	57	49	57	59	39	59	66	57
	Max	2500	124	1452	1332	353	85	652	2880	175550	236
	90th Perc.	1018	101	216	700	231	45	364	683	128838	60
	50th Perc.	322	7.9	140	189	102	2.4	254	152	69100	19
	10th Perc.	118	7.4	62	91	47	<0.17	59	63	33575	9.0
	Min	55	7.3	45	44	23	<0.17	<43.5	25	17000	4
Bottom Ash		As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Sb	Be
	# Sites	37	37	37	37	37	160	37	37	37	152
	Max	56	9360	<5.5	4710	843	1.3	8.2	7.5	8.4	568
	90th Perc.	21	3604	<5.5	1132	53	0.080	4.2	<5.5	<7	14
	50th Perc.	7.2	768	<5.5	191	20	0.018	<1.25	<5.5	<7	5.8
	10th Perc.	2.6	378	<5.5	51	8.1	0.004	<1.25	<5.5	<7	0.208
	Min	<1.3	<61	<5.5	<24	<2.1	<0.002	<1.25	<5.5	<7	<0.064
		B	Co	Cu	Mn	Ni	Tl	V	Zn	Fe	Mo
	# Sites	76	NA	37	37	37	21	37	37	37	37
	Max	990	NA	146	1940	1267	59	275	717	199500	46
	90th Perc.	335	NA	118	892	445	0.88	250	367	158850	27
	50th Perc.	82	NA	73	262	123	<0.5	161	59	101200	11
	10th Perc.	2.7	NA	39	85	39	<0.5	<50	16	40339	3.9
	Min	<2.04	NA	20	73	<12	<0.5	<50	3.8	21600	<1.4
FGD Gypsum		As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Sb	Be
	# Sites	27	27	26	27	27	27	27	1	26	27
	Max	11	55	0.37	24	2.0	1.5	32	<4.9	2.0	<0.1
	90th Perc.	5.9	22	0.21	6.7	<1	0.801	24	<4.9	<0.4	<0.1
	50th Perc.	2.9	6.1	0.07	2.4	<1	0.200	4.2	<4.9	<0.4	<0.1
	10th Perc.	2.1	2.6	<0.02	0.83	<1	0.035	<2.5	<4.9	<0.4	<0.1
	Min	<1.9	0.91	<0.02	0.60	<1	0.0075	<2.5	<4.9	<0.4	<0.1
		B	Co	Cu	Mn	Ni	Tl	V	Zn	Fe	Mo
	# Sites	26	26	26	27	26	26	26	26	26	26
	Max	387	<1	3.2	129	2.4	<0.05	8.6	23	1823	3.1
	90th Perc.	93	<1	2.2	47	2.1	<0.05	4.1	14	1611	1.7
	50th Perc.	<25	<1	1.1	8.8	1.1	<0.05	<1	5.4	800	0.53
	10th Perc.	<25	<1	<0.4	<1	0.6	<0.05	<1	<1.25	296	0.17
	Min	<25	<1	<0.4	<1	<0.2	<0.05	<1	<1.25	130	<0.02

NA – Data Not Available

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Table 2-2
Statistical summary of the concentrations of various elements in other materials (all concentrations in mg/kg)

Rock	As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Sb	Be
# Samples	18149	31706	27	31384	4257	120	167	1200	30134	1175
Max	138000	537000	5.8	37000	63000	10	20	770	44200	48
90th Perc.	14	1390	3.6	309	44	2	4.9	3	1.8	4.4
50th Perc.	1.6	420	<2	28	15	0.7	1.9	0.90	0.30	1.3
10th Perc.	0.5	67	<2	1.9	3.8	0.1	0.60	0.03	0.08	0.10
Min	<0.0087	0.13	<2	0.14	<0.1	0.03	<0.13	<0.01	<0.0019	<0.008
	B	Co	Cu	Mn	Ni	Tl	V	Zn	Fe	Mo
# Samples	3126	31504	26873	1714	22875	1177	4376	29636	NA	4263
Max	78000	29100	104000	610000	88300	24.8	2730	354000	NA	640
90th Perc.	220	53	122	1740	220	1.8	232	138	NA	18
50th Perc.	0.33	16	30	430	18	0.50	52	72	NA	1.6
10th Perc.	<0.2	0.86	10	49	2.0	0.10	2.6	25	NA	0.24
Min	<0.2	0.02	<0.5	0.09	0.09	<0.003	<0.1	0.11	NA	<0.05
Soil	As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Sb	Be
# Samples	1258	1320	830	1320	1320	1268	1268	830	355	1304
Max	97	5000	8.2	2000	700	4.6	4.32	<1	8.78	15
90th Perc.	12	1000	0.5	100	30	0.19	0.8	<1	1.3	2
50th Perc.	5.8	500	0.2	50	15	0.05	0.3	<1	<1	<1
10th Perc.	2.0	200	<0.1	15	<10	0.02	<0.1	<1	<1	<1
Min	<0.1	10	<0.1	<1	<10	<0.02	<0.1	<1	<1	<1
	B	Co	Cu	Mn	Ni	Tl	V	Zn	Fe	Mo
# Samples	1320	1324	1312	1318	1319	830	1320	1249	NA	1299
Max	300	70	700	7000	700	1.8	500	2890	NA	15
90th Perc.	70	15	50	1000	30	0.7	150	99	NA	<3
50th Perc.	30	7	20	300	15	0.5	70	50	NA	<3
10th Perc.	<20	<3	5	100	5	0.2	20	22	NA	<3
Min	<20	<3	<1	<2	<3	<0.1	<7	<5	NA	<3
Foundry Sand	As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Sb	Be
# Samples	43	43	43	43	43	43	43	43	43	43
Max	4.8	151	<5.9	149	26	NA	NA	<17.6	<4.5	3.1
90th Perc.	1.98	35	<5.9	35	<7.7	NA	NA	<17.6	<4.5	1.24
50th Perc.	0.83	15	<5.9	2.8	<7.7	NA	NA	<17.6	<4.5	<1.2
10th Perc.	0.14	4.35	<5.9	1.5	<7.7	NA	NA	<17.6	<4.5	<1.2
Min	0.04	<8.7	<5.9	<1	<7.7	NA	NA	<17.6	<4.5	<1.2
	B	Co	Cu	Mn	Ni	Tl	V	Zn	Fe	Mo
# Samples	43	43	43	43	43	43	43	43	43	43
Max	<19.2	95	3318	671	2328	NA	9.1	1640	NA	NA
90th Perc.	<19.2	1.66	62	194	28	NA	<7.4	<33.4	NA	NA
50th Perc.	<19.2	<0.84	<23.1	<45	2.8	NA	<7.4	<33.4	NA	NA
10th Perc.	<19.2	<0.84	<23.1	<45	1.5	NA	<7.4	<33.4	NA	NA
Min	<19.2	<0.84	<23.1	<45	<1.2	NA	<7.4	<33.4	NA	NA
Biosolids	As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Sb	Be
# Samples	84	84	84	84	84	84	84	84	84	84
Max	49.2	3460	11.8	1160	450	8.26	24.7	856	27	2.34
90th Perc.	13	1183	6.96	213	171	2.58	13	39	4.02	0.86
50th Perc.	5.08	431	1.75	35	49	0.85	6.2	14	1.62	0.28
10th Perc.	2.61	200	0.97	14.4	21	0.33	3	3.54	0.05	0.10
Min	1.18	75	0.21	6.74	5.81	0.17	1.1	1.94	<0.04	0.04
	B	Co	Cu	Mn	Ni	Tl	V	Zn	Fe	Mo
# Samples	84	84	84	84	84	84	84	84	84	84
Max	204	290	2580	14900	526	1.68	617	8550	NA	132
90th Perc.	106	15.99	955	2945	117	0.37	98	1561	NA	36
50th Perc.	33	4.63	468	433	24	0.13	14	803	NA	11
10th Perc.	9.49	1.79	167	152	11	0.05	6.84	379	NA	4.05
Min	5.7	0.87	115	35	7.44	0.02	2.04	216	NA	2.51
Fertilizers	As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Sb	Be
Min	<2	<2	<0.02	<0.5	<1.5	<0.003	<1	<0.01	<0.1	<0.011
Max	4600	704	201	840	1480	2.91	44	6.32	12.2	4.66
	B	Cu	Mn	Co	Ni	Tl	V	Zn	Fe	Mo
Min	<15	<1.5	<2.5	0.25	<0.15	<0.15	<1	<5	NA	<0.04
Max	123644	3620	9641	62	517	3.9	949	460564	NA	39
Metal slags	As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Sb	Be
# Samples	73	73	73	73	73	73	73	73	73	73
Min	0.5	24	0.1	10	1.4	0.1	2.2	1.3	1.1	0.6
Max	5.8	1800	19	6200	330	0.1	36	100	18	11
	B	Co	Cu	Mn	Ni	Tl	V	Zn	Fe	Mo
# Samples	73	73	73	73	73	73	73	73	73	73
Min	NA	0.9	1.7	100	2.1	11	170	3.5	NA	0.8
Max	NA	13	540	65700	310	11	1700	690	NA	81

NA – Data Not Available

3
ROCKS

Information Sources

Trace element concentration data for rocks are provided in many different sources, including, but not limited to:

- United States Geological Survey, 2009. ***Geochemistry of rock samples from the National Geochemical Database.*** U.S. Geological Survey, Reston, VA.
- Blatt and Tracy (eds), 1996. ***Petrology: Igneous, Sedimentary and Metamorphic***, 2nd Ed. W.H. Freeman and Company, 529 pp.
- Horn, M.K. and Adams, J.A.S., 1966. ***Computer-derived geochemical balances and elemental abundances***. Geochimica et Cosmochimica Acta, Vol. 30, pp. 279-297. ***In*** Hem, J.D., 1992. ***Study and Interpretation of the Chemical Characteristics of Natural Water***. U.S. Geological Survey Professional Paper 2254.
- Taylor, H.E., and F.E. Lichte, 1980. ***Chemical composition of Mount St. Helens volcanic ash***. Geophysical Research Letters, Vol. 7, No. 11, pp. 949-952.
- Cannon, H.L., 1978. ***Report of the workshop at South Seas Plantation Captiva Island, Florida***, Geochemistry and the Environment 3 (1978), pp. 17–31. ***In*** Adriano, D.C. (ed), 2001. ***Trace Elements in the Terrestrial Environment,*** Springer-Verlag, New York.

In the current evaluation, the major chemical compositions of CCPs and rocks are compared using data from Blatt and Tracy (1996) and Horn and Adams (1966). Trace element concentrations in CCPs are compared to those in "rocks," a collective term for all rock types, including igneous, metamorphic, and sedimentary, using data from USGS (2009). CCPs are compared separately to volcanic ash using data reported by Taylor and Lichte (1980).

Bulk Chemical Composition

Fly ash and bottom ash are most similar in bulk chemical composition to siliceous rocks, and the greatest similarity is observed between fly ash and bottom ash and rocks such as volcanic ash and shale (Figure 3-1). The overall chemical composition of coal ash resembles that of siliceous rocks from which it was derived, particularly shale. Oxides of silicon, aluminum, iron, and calcium make up more than 90% of most siliceous rocks, soils, fly ash, and bottom ash. Other major and minor elements (sulfur, sodium, potassium, magnesium, titanium) make up an additional 8%, while trace constituents account for less than 1%.

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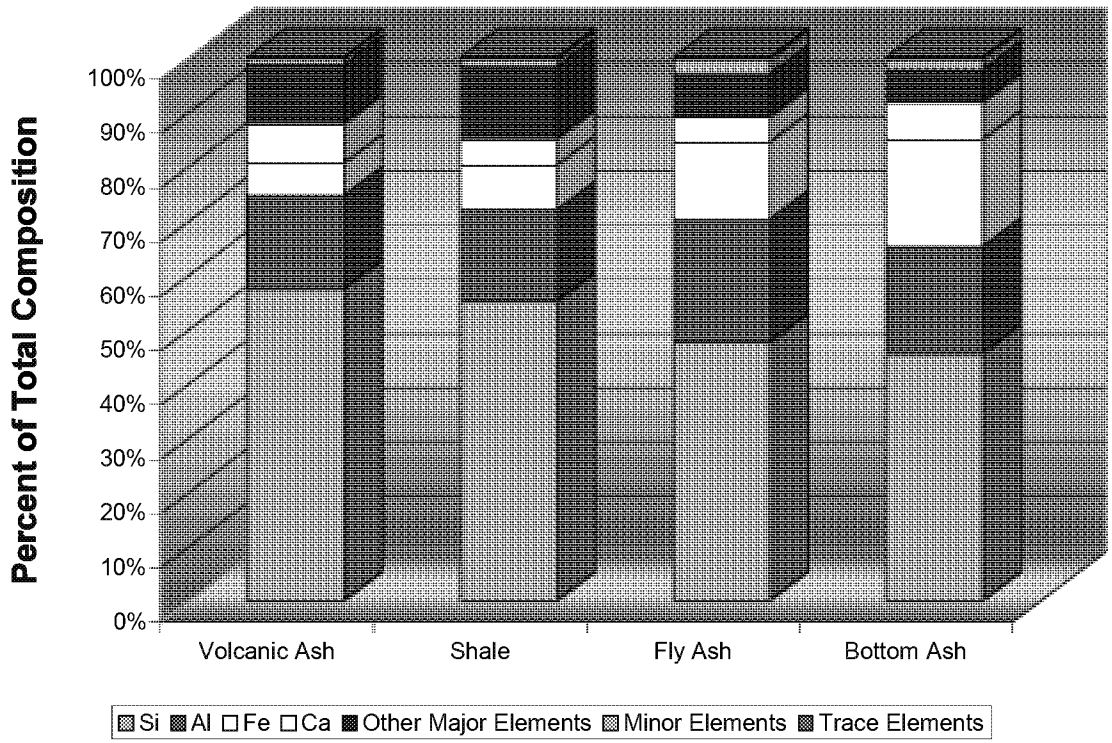

Figure 3-1
Bulk chemical composition of volcanic ash, shale, and coal ash

Trace Element Concentration Ranges

Data Source Considerations

USGS (2009) data are available from a comprehensive dataset referred to as the "National Geochemical Database: Rocks," containing 414,321 records. The reliability of the data source and the wealth of data contained in the database make this source preferable to others for the current study. Downloadable data are distributed in files unique to the analytical method used to produce the data. For example, the x-ray fluorescence (XRF), instrumental neutron activation analysis (INAA), inductively coupled plasma–atomic emission spectrometry (ICP-AES), or inductively coupled plasma–mass spectrometry (ICP-MS) spreadsheets may be downloaded separately. The data query by method allows the user to choose the analytical method best suited for the element of concern. The USGS web page directs the user toward the most appropriate dataset for a particular element with the following statement, where arsenic is an example:

> "Analytical methods for arsenic are listed in a general order of preference based on method consistency, reliability, and detection limits. All total digestion methods are listed before any partial digestion methods."

The user then downloads the most appropriate dataset for the element of concern, based upon the attributes described above. By doing so, the user possesses a reliable dataset that is also amenable to data analysis.

In this study, trace element concentration ranges as percentiles were calculated based upon the analytical method dataset most appropriate for that element (i.e., listed first in order of preference by the USGS). For example, the arsenic 10th and 90th percentiles are based only on data contained in the INAA dataset, whereas manganese data are evaluated from the ICP-AES dataset.

Trace Element Comparisons to Fly Ash, Bottom Ash, and FGD Gypsum

Trace element concentration ranges of CCPs are compared to those of rocks in Figures 3-2 to 3-4. All comparisons are summarized in Table 3-1. Trace element concentrations in fly ash are generally higher than in rocks, concentrations in bottom ash are comparable to or higher than in rocks, and concentrations in FGD gypsum are generally comparable to or less than in rocks.

When minima and maxima data are used, trace element concentration ranges in fly ash plot within the concentration ranges of rock, with the exceptions of cadmium, selenium, beryllium, and thallium. However, the use of minima and maxima is not recommended in this case. For example, in the case of arsenic in rocks, the maximum for rocks is 138,000 mg/kg, but the 99th percentile is 323 mg/kg—a difference of three orders of magnitude that biases the comparison. Therefore, the use of the 10th and 90th percentiles is more appropriate.

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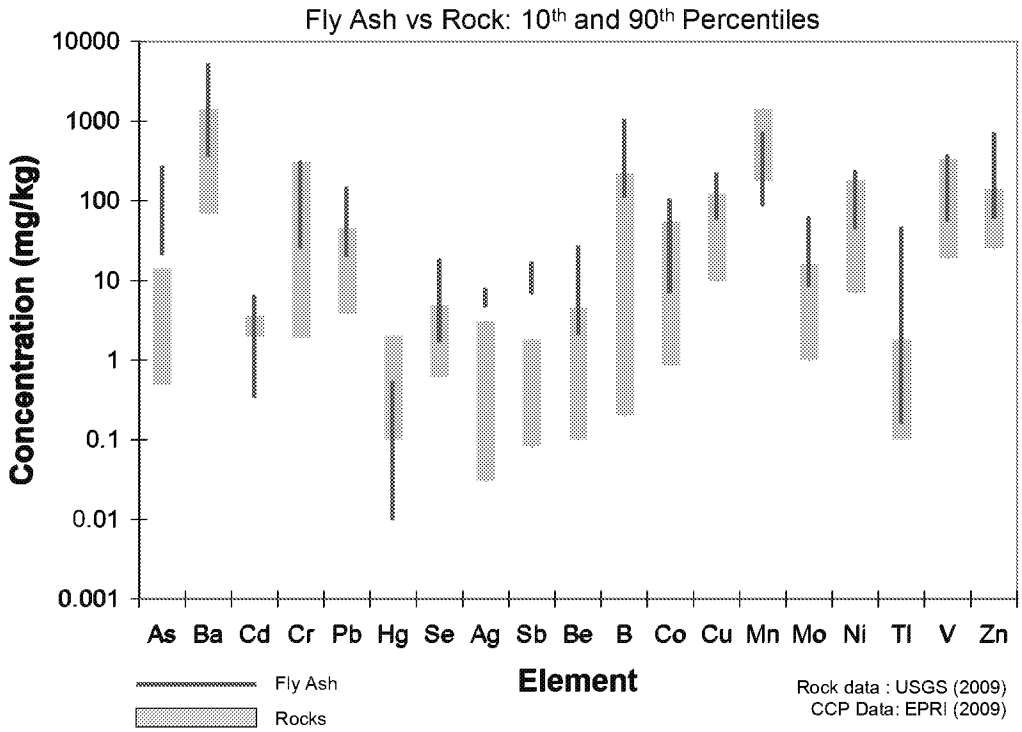

Figure 3-2
Trace element concentration ranges in rocks and fly ash

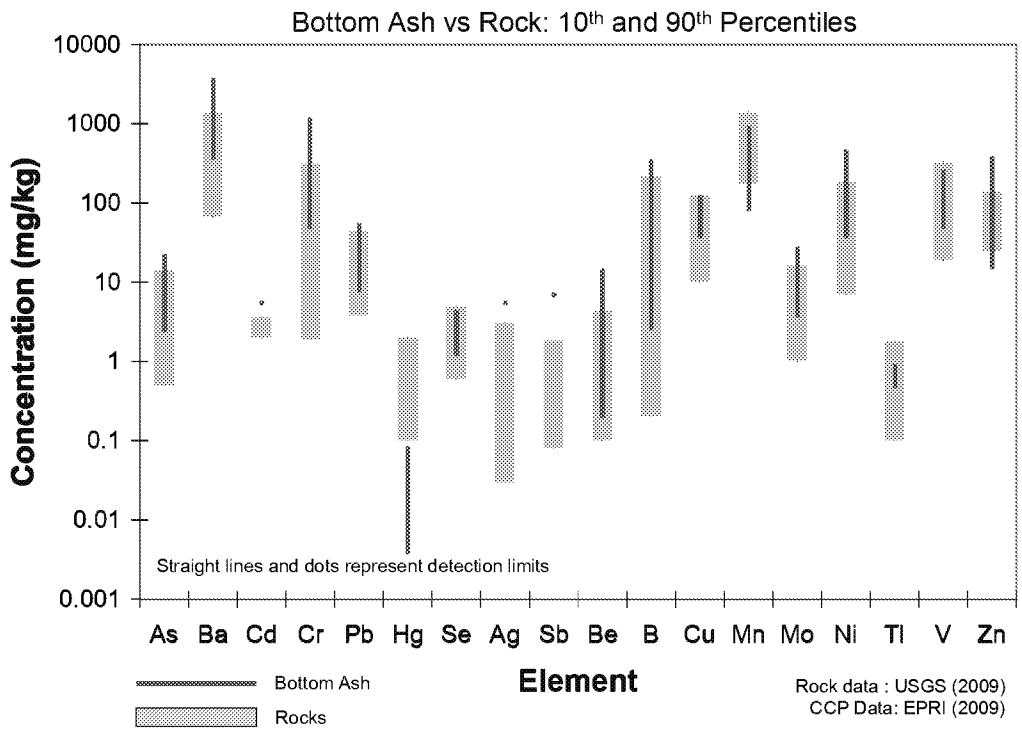

Figure 3-3
Trace element concentration ranges in rocks and bottom ash

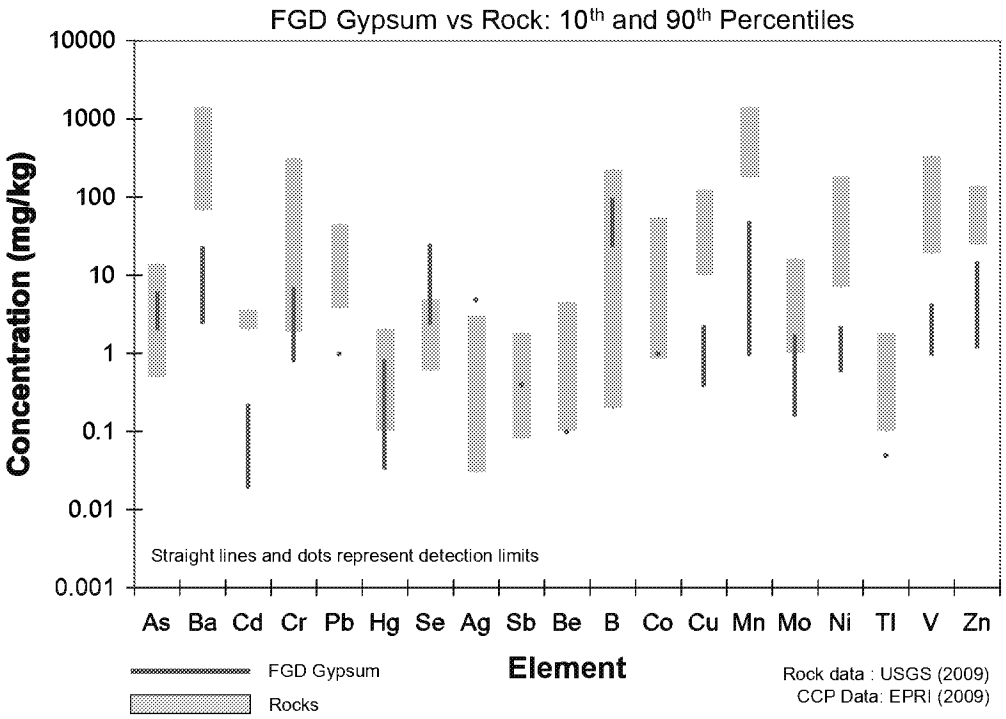

Figure 3-4
Trace element concentration ranges in rocks and FGD gypsum

Table 3-1
Concentration comparisons summary for CCPs and rocks (10th to 90th percentile ranges)

Graphical Comparison	Fly Ash	Bottom Ash	FGD Gypsum
Above range	As, Ag, Sb		
Overlapping higher	Ba, Pb, Se, Be, B, Co, Cu, Mo, Ni, Tl, V, Zn	As, Ba, Cr, Pb, Be, B, Mo, Ni	Se
Overlapping	Cd	Zn	
Within	Cr	Se, Cu, Tl, V	As, B
Overlapping lower	Hg, Mn	Mn	Cr, Hg, Co, Mo
Below range		Hg	Ba, Cd, Pb, Be, Cu, Mn, Ni, Tl, V, Zn
Unable to compare due to all non-detects		Cd, Ag, Sb	Ag, Sb

Key:
CCPs
Rocks

4
SOILS

Information Sources

Two primary sources of soil composition data exist for the United States:

- United States Geological Survey (Shacklette and Boerngen), 1984. ***Element concentrations in soils and other surficial materials of the coterminous United States: An account of the concentrations of 50 chemical elements in samples of soils and other regoliths***. U.S. Geological Survey Professional Paper 1270.
- United States Geological Survey (Smith et al.), 2005. ***Major- and trace-element concentrations in soils from two continental scale transects of the United States and Canada.*** U.S. Geological Survey Open-File Report 2005-1253.

The choice of dataset used for comparison is discussed in detail below.

Comparison of Soil Data Sources

Each study proposed to establish "baseline" soil concentrations across the United States. USGS (1984) accomplished this by sampling surface soils across the entire coterminous United States, but at a relatively low sampling density (shown as circles in Figure 4-1). USGS (2005) sampled soils along two transects (North-South and East-West), but at a higher sampling density (shown as solid line transects in Figure 4-1). The following discussion describes advantages and disadvantages to using either study as a primary data source, without rigorous statistical analysis of the data.

The benefits of using USGS (1984) as the primary dataset are:

- The study sampled more total sites (1,323) than USGS (2005) (265). More data provide greater confidence for calculations, and it is more likely that the dataset will capture the total concentration range for a particular element. For example, the highest arsenic concentration in the USGS (2005) dataset is 23 mg/kg, compared to 97 mg/kg in the USGS (1984) study;
- The study included more elements (50) than the USGS (2005) study (42);
- Sample locations were spread across the entire coterminous United States, providing more coverage of factors that influence soil development and chemistry—specifically time, climate, topography, and parent materials (rocks). For example, USGS (2005) appears to entirely neglect volcanic soils, and may focus too heavily on prairie soils (Figure 4-2);
- The study included boron, a commonly found element in CCPs, but USGS (2005) did not;

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- The study made a deliberate attempt to avoid sampling disturbed agricultural soils in an effort to present only data that may be considered "pristine." This is beneficial because the goal of this study is not to compare CCPs to soils affected by anthropogenic sources, but to naturally occurring soils; and
- Detection limits for arsenic, manganese, and selenium are lower than in the USGS (2005) study. These elements are commonly found in CCPs, and can be the focus of regulatory concerns.

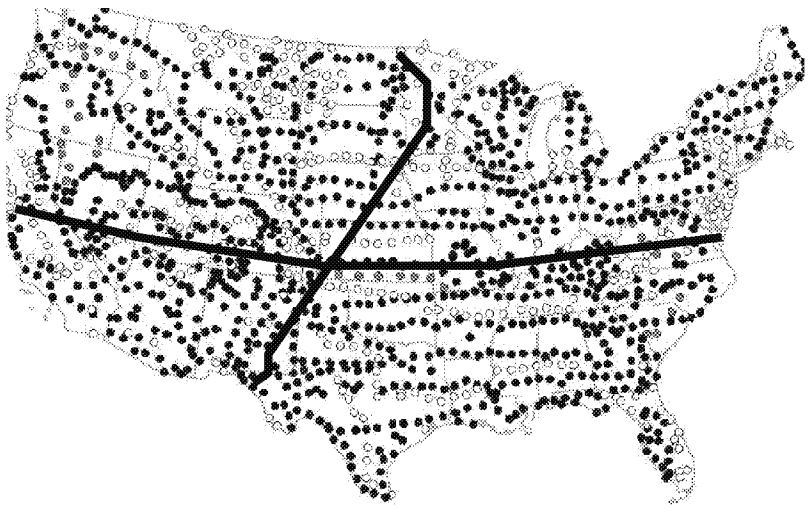

Figure 4-1
Sample locations in USGS (1984) (shown as circles) and USGS (2005) (shown as solid line transects). Figure modified after USGS (2001). Different-color circles represent separate sample collection efforts that are summarized in USGS (1984).

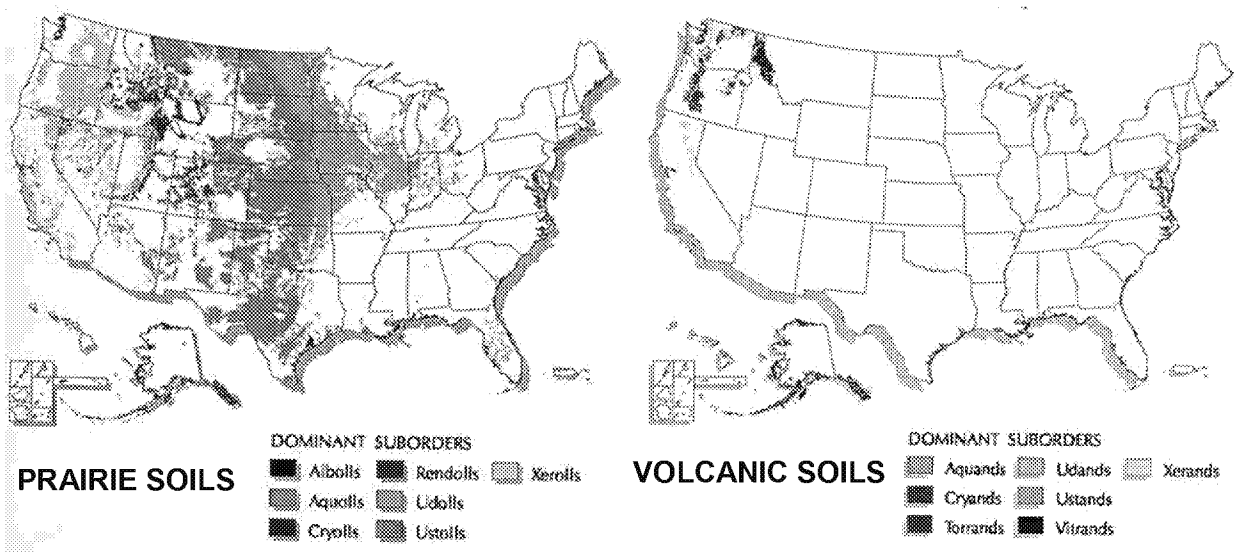

Figure 4-2
Distribution of prairie and volcanic soils in the United States (USDA, 2009)

The benefits of using USGS (2005) as the primary dataset are:

- The study included thallium, silver, and cadmium, but USGS (1984) did not;
- The study has been used in recent risk assessment activities, such as that performed by the U.S. Department of Agriculture for spent foundry sands;
- Detection limits for cobalt, molybdenum, nickel, lead, antimony, vanadium, and zinc are lower—in some cases substantially lower—than in the USGS (1984) study; and
- The sample density is higher than in USGS (1984). For this study, increased sample density may not play an important role if the overall number of samples is lower, and many geographic areas of the United States were excluded. However, if the study is amended with future attempts to increase areal sample coverage, then increased sample density would be beneficial.

Despite their differences, using one dataset and not the other may not produce significantly different results. For example, the 10th and 90th percentile values of multiple elements are similar, suggesting that an increased total number of samples did not produce significant changes in an element's concentration range when viewed as percentile values (Figure 4-3). The minimum and maximum values show less agreement, suggesting that either detection limit differences or differences in total sample numbers produce less comparability at concentration range extremes (potential outliers). Furthermore, mean and median values from each dataset show generally good agreement and closeness to the 1:1 line (Figure 4-4).

The USGS (1984) study was chosen as the primary dataset for comparisons, substituting USGS (2005) data for thallium, silver, and cadmium. The reasoning is as follows:

- USGS (1984) offers a more thorough analysis of the entire coterminous United States, including more major soil types, climatic zones, and parent materials (rocks);
- USGS (1984) attempted to exclude potentially contaminated soils in an effort to describe "baseline" concentrations. Although this may not have been totally achievable, it helps to ensure that CCPs are compared to naturally occurring concentrations in soils;
- Arsenic and selenium detection limits in USGS (1984) were lower, providing a more conservative comparison to CCPs;
- Higher sample density is not believed to improve the dataset quality for comparisons to CCPs; and
- Both datasets produce similar summary statistics, including 10th and 90th percentile, median, and mean values.

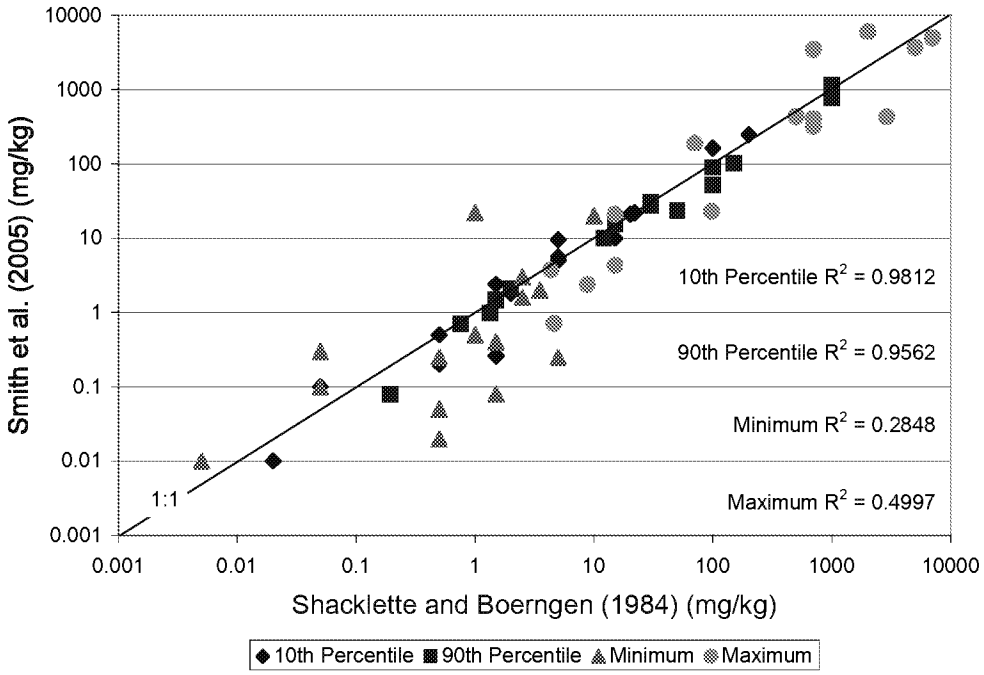

Figure 4-3
Comparison of minimum, maximum, 10th percentile, and 90th percentile concentration values in the USGS (1984) and USGS (2005) datasets (see Table 4-1)

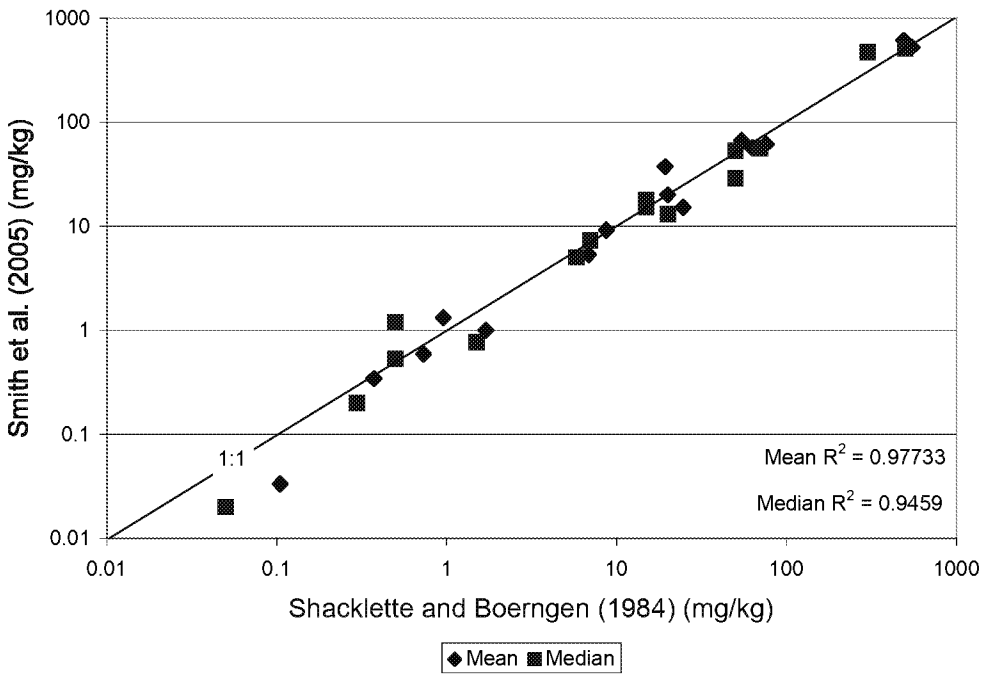

Figure 4-4
Comparison of mean and median concentration values in the USGS (1984) and USGS (2005) datasets

Table 4-1
Summary statistics for soil trace element concentrations reported in USGS (1984) and USGS (2005) (data in mg/kg)

	Mean		Median		Min		Max		10th Percentile		90th Percentile		Detection Limits	
Element	*S&B*	*Smith*	*S&B*	*Smith*	*S&B*	*Smith*	*S&B*	*Smith*	*S&B*	*Smith*	*S&B*	*Smith*	*S&B*	*Smith*
Ag		<1		<1		<1		<1		<1		<1	1	1
As	6.9	5.3	5.8	5.0	<0.1	0.3	97	23	2.0	1.8	12	10	0.1	1
B	32		30		<20		300		<20		70		20	
Ba	546	526	500	508	10	20	5000	3670	200	249	1000	777		
Be	1.0	1.3	0.5	1.2	0.5	<0.1	15	4.3	0.5	0.5	2.0	2.1	0.1	0.1
Cd		0.28		0.20		0.04		8.2		<0.1		0.50		0.1
Co	8.7	9.2	7.0	7.3	<3	0.4	70	191	<3	2.4	15	16	3	0.1
Cr	54	67	50	29	1	<1	2000	6030	15	10	100	52		1
Cu	25	15	20	13	<1	<0.5	700	404	5.0	5.0	50	23	1	0.5
Hg	0.10	0.03	0.05	0.02	<0.02	<0.02	4.6	0.71	0.02	<0.02	0.19	0.08	0.02	0.02
Mn	489	611	300	468	1	22	7000	4966	100	163	1000	1140	2	5
Mo	<3	1.0	<3	0.77	1.5	0.08	15	21	<3	0.26	1.5	1.48	3	0.05
Ni	19	37	15	15	<3	1.6	700	3447	5.0	5.6	30	31	3	0.5
Pb	20	20	15	18	5.0	<0.5	700	319	<10	9.6	30	27	10	0.5
Sb	<1	0.6	<1	0.53	<1	<0.05	8.8	2.4	<1	0.20	1.3	0.98	1	0.05
Se	0.37	0.34	0.30	0.20	<0.1	<0.2	4.3	3.7	<0.1	<0.2	0.75	0.70	0.1	0.2
Tl		0.45		0.47		<0.1		1.8		0.20		0.70		0.1
V	76	61	70	56	3.5	2	500	430	20	21	150	101	7	1
Zn	63	57	50	53	2.5	3	2890	433	22	22	99	90	5	1

"S&B" refers to Shacklette and Boerngen (1984) and "Smith" refers to Smith et al. (2005).
Blank cells indicate that data were not reported.
Data plotted in Figures 4-3 and 4-4 as 1/2 DL if value is less than DL.

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Trace Element Concentration Ranges

Trace element concentration ranges of CCPs are compared to those of soil in Figures 4-5 to 4-7. All comparisons are summarized in Table 4-2. Most elements exhibit higher concentration ranges in fly ash and bottom ash compared to soils. Concentrations in FGD gypsum are generally less than in soils, except for selenium and mercury.

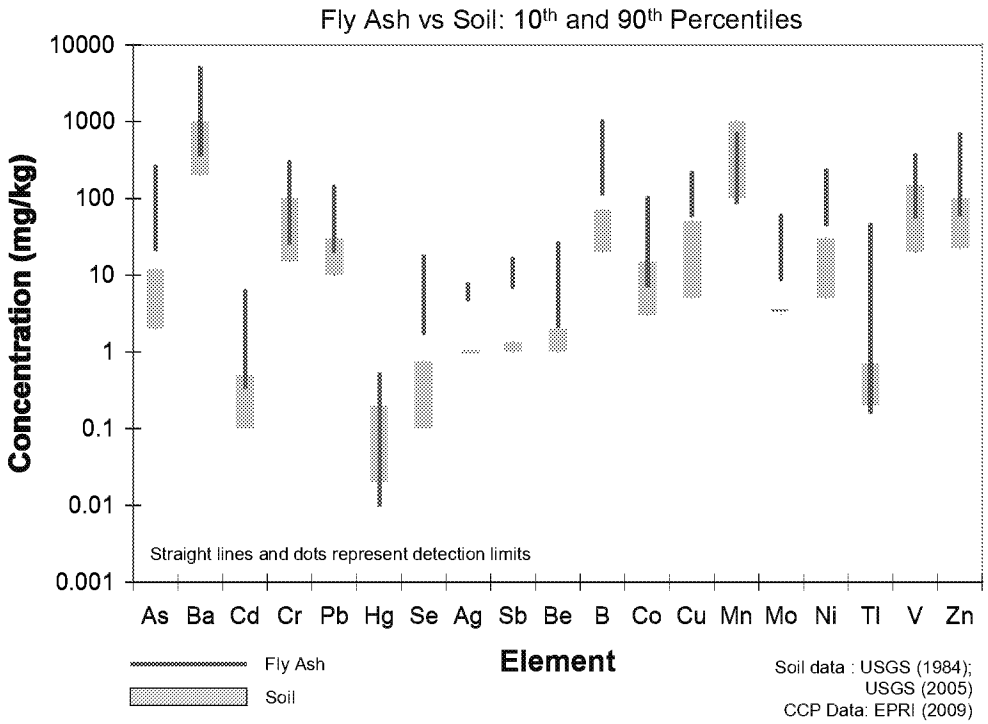

Figure 4-5
Trace element concentration ranges in U.S. soils and fly ash

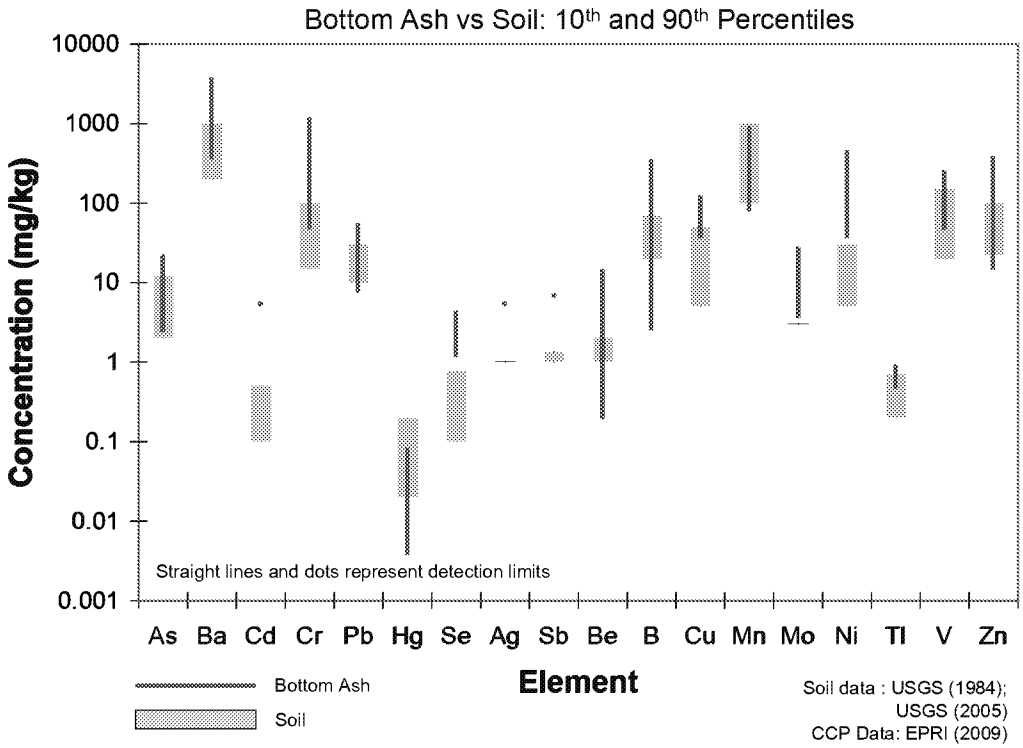

Figure 4-6
Trace element concentration ranges in U.S. soils and bottom ash

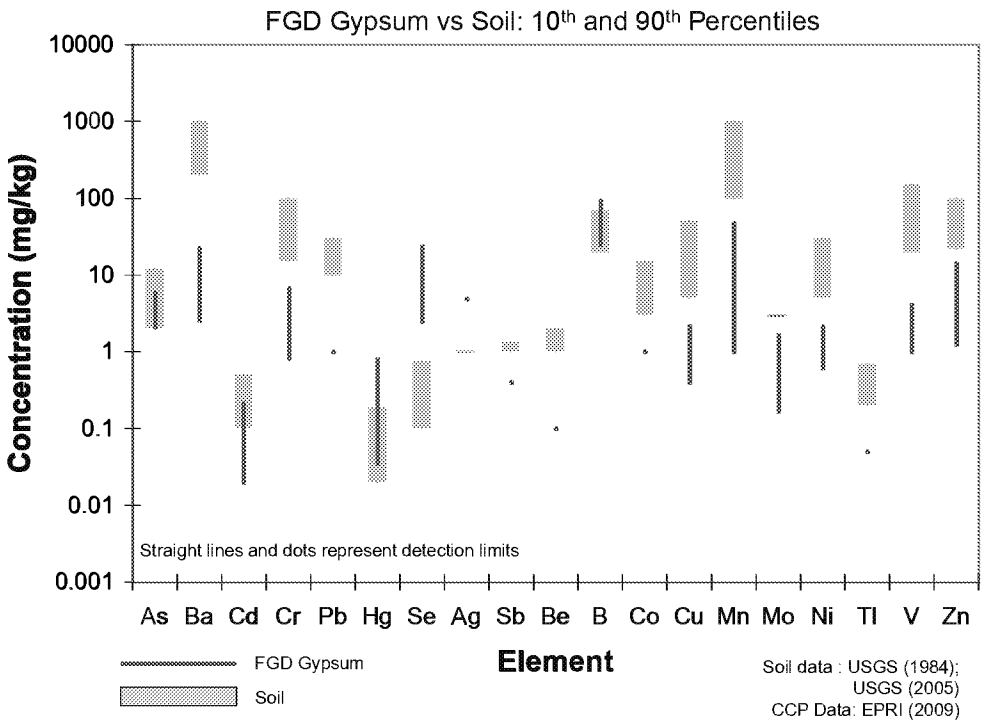

Figure 4-7
Trace element concentration ranges in U.S. soils and FGD gypsum

Table 4-2
Concentration comparisons summary for CCPs and soils

Comparison	Fly Ash	Bottom Ash	FGD Gypsum
Above range	As, Se, Ag, Sb, Be, B, Cu, Ni, Mo	Se, Mo, Ni	Se
Overlapping higher	Ba, Cd, Cr, Pb, Co, V, Zn	As, Ba, Cr, Cu, Tl, V	Hg, B
Overlapping	Hg, Tl	Pb, Be, B, Zn	
Within			As
Overlapping lower	Mn	Hg, Mn	Cd
Below range			Ba, Cr, Pb, Sb, Be, Co, Cu, Mn, Ni, Tl, V, Zn
Unable to compare due to all non-detects		Cd, Ag, Sb	Ag, Mo

Key:
CCPs
Soils

5
FERTILIZERS

Information Sources

No single data source provided all necessary information to compare fertilizers and CCPs. The following data sources contain information relevant to the current study:

- U.S. Environmental Protection Agency, January 1999. ***Background Report on Fertilizer Use, Contaminants and Regulations***. Office of Pollution Prevention and Toxics. EPA 747-R-98-003.
- Shaffer, M., 2001. ***Waste Lands: The Threat of Toxic Fertilizer***. California Public Interest Research Group Charitable Trust.
- U.S. Environmental Protection Agency, August 1999. ***Estimating Risk from Contaminants Contained in Agricultural Fertilizers***. Office of Solid Waste. EPA 68-W-98-0085.
- Washington State Department of Ecology, 1997. ***Screening survey for metals in fertilizers and industrial by-product fertilizers in Washington State***. Ecology Publication #97-341. December 1997.
- Washington State Department of Agriculture, 2009. ***Metals analysis conducted by WSDA***. Accessed online 9/16/09 at http://agr.wa.gov/PestFert/Fertilizers/Metals.aspx.
- Minnesota Department of Agriculture, 2009. ***MDA fertilizer heavy metal analysis reports***. Accessed online 9/16/09 at http://www.mda.state.mn.us/chemicals/fertilizers/heavymetals.htm.
- Minnesota Department of Health, 2009. ***Heavy metals in fertilizers***. Accessed online 9/16/09 at http://www.health.state.mn.us/divs/eh/risk/studies/metals.html.

Calculations of percentile values were not performed due to the wide variability in reported fertilizer types and manufacturers. Fertilizers are compared to CCPs on the basis of minima and maxima concentrations.

Trace Element Concentration Ranges

Trace element concentration ranges of CCPs are compared to those of fertilizers in Figures 5-1 to 5-3. All comparisons are summarized in Table 5-1. Fly ash and bottom ash concentrations are generally comparable to or slightly higher than those of fertilizers. Concentrations in FGD gypsum are typically comparable to or lower than those of fertilizers.

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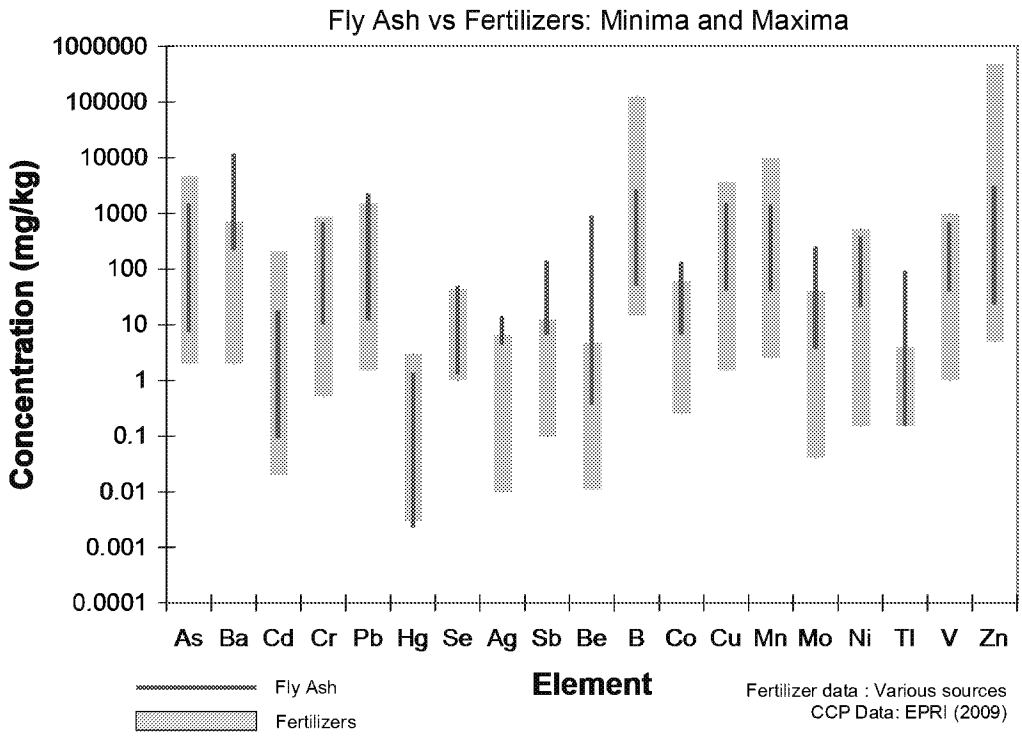

Figure 5-1
Trace element concentration ranges in fly ash and fertilizers compared as minima and maxima

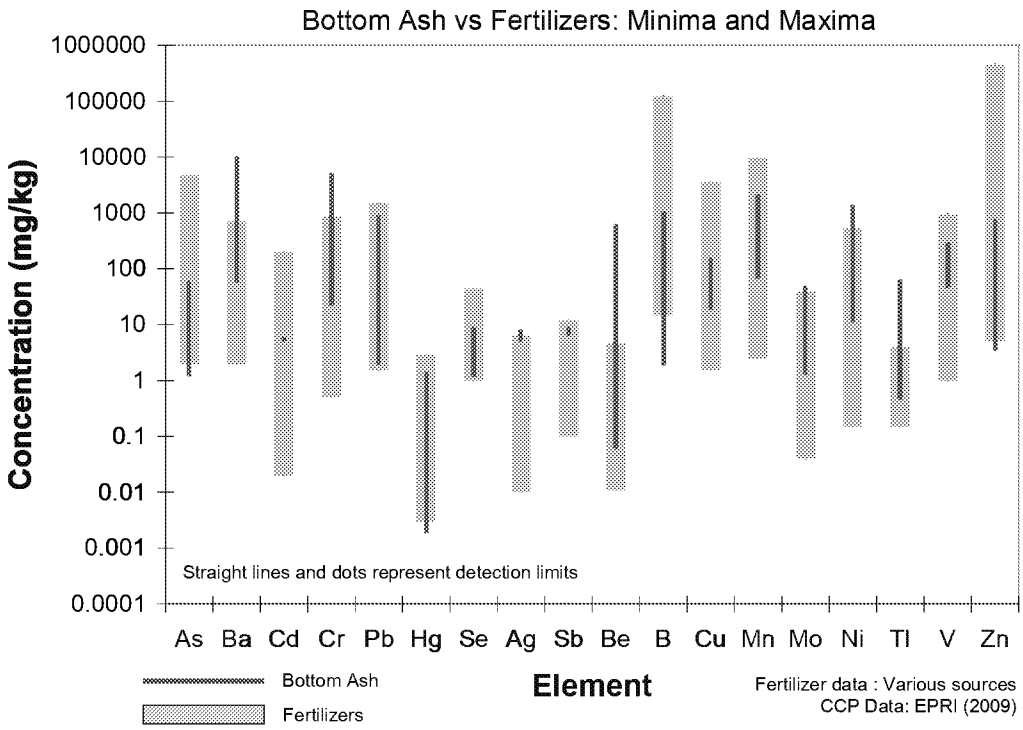

Figure 5-2
Trace element concentration ranges in bottom ash and fertilizer compared as minima and maxima

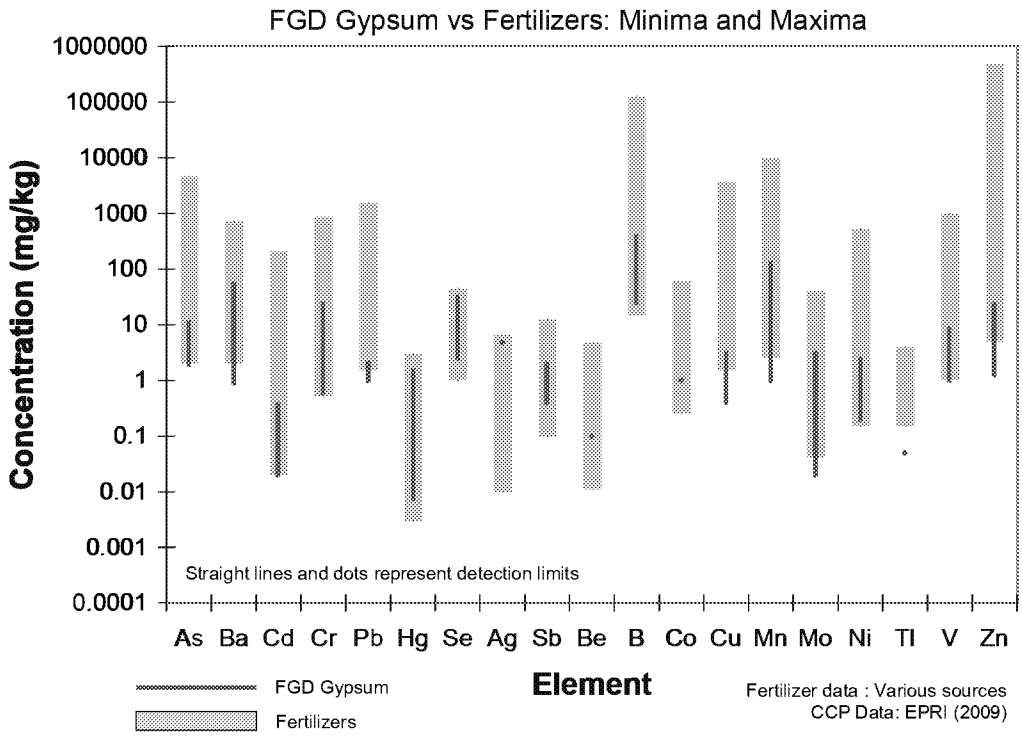

Figure 5-3
Trace element concentration ranges in FGD gypsum and fertilizer compared as minima and maxima

Table 5-1
Concentration comparisons summary for CCPs and fertilizers

Comparison	Fly Ash	Bottom Ash	FGD Gypsum
Above range			
Overlapping higher	Ba, Pb, Se, Ag, Sb, Be, Co, Mo, Tl	Ba, Cr, Ag, Be, Mo, Ni, Tl	
Overlapping			
Within	As, Cd, Cr, B, Cu, Mn, Ni, V, Zn	Pb, Se, Cu, Mn, V, Sb	Cr, Hg, Se, Sb, B, Ni
Overlapping lower	Hg	As, Hg, B, Zn	As, Ba, Cd, Pb, Cu, Mn, Mo, V, Zn
Below range			Tl
Unable to compare due to all non-detects		Cd	Ag, Be, Co

Key:
CCPs
Fertilizers

6
METAL SLAGS

Information Sources

The chemical characteristics of metal slags (blast furnace, basic oxygen furnace, and electric arc furnace) are described in detail in the following study:

- Proctor, D.M., K.A. Fehling, E.C. Shay, J.L. Wittenborn, J.J. Green, C. Avent, R.D. Bigham, M. Connolly, B. Lee, T.O. Shepker, and M.A. Zak, 2000. ***Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen Furnace, and Electric Arc Furnace Steel Industry Slags***. Environmental Science & Technology, Volume 34, No. 8, pp. 1576-1582.

Iron and steel slag are produced as the nonmetallic co-product of iron and steel production. The industry produces three main slag types: blast furnace, basic oxygen furnace, and electric arc furnace slag. Each is composed primarily of fluxing agents such as lime, and the molten impurities of iron or steel (Proctor et al., 2000).

The report contains data for slag samples from 58 active mills, including sites that produced approximately 47% of steel industry slag in North America. It provides total metals composition and leachate characteristics, representing the most complete characterization of steel slag produced in North America at the time of its publication. No more current or complete study was found during the literature review for this report.

In the Proctor et al. (2000) report, the individual data were not reported, but were presented in summary form. The current comparison is limited to comparing minima and maxima for concentration range bounds. Also, blast furnace, basic oxygen furnace, and electric arc furnace are all referred to collectively as "metal slags" for comparison.

Trace Element Concentration Ranges

Trace element concentration ranges of CCPs are compared to those of metal slags in Figures 6-1 to 6-3. All comparisons are summarized in Table 6-1. Fly ash concentrations are generally comparable to or slightly higher than metal slag concentrations. Bottom ash concentrations are comparable to metal slag concentrations. Concentrations in FGD gypsum are typically lower than in metal slags.

TCLP leachate concentrations are plotted in Figure 6-4. Coal ash leachate concentrations overlap those of metal slags, although the fly ash ranges are larger for about half of the constituents.

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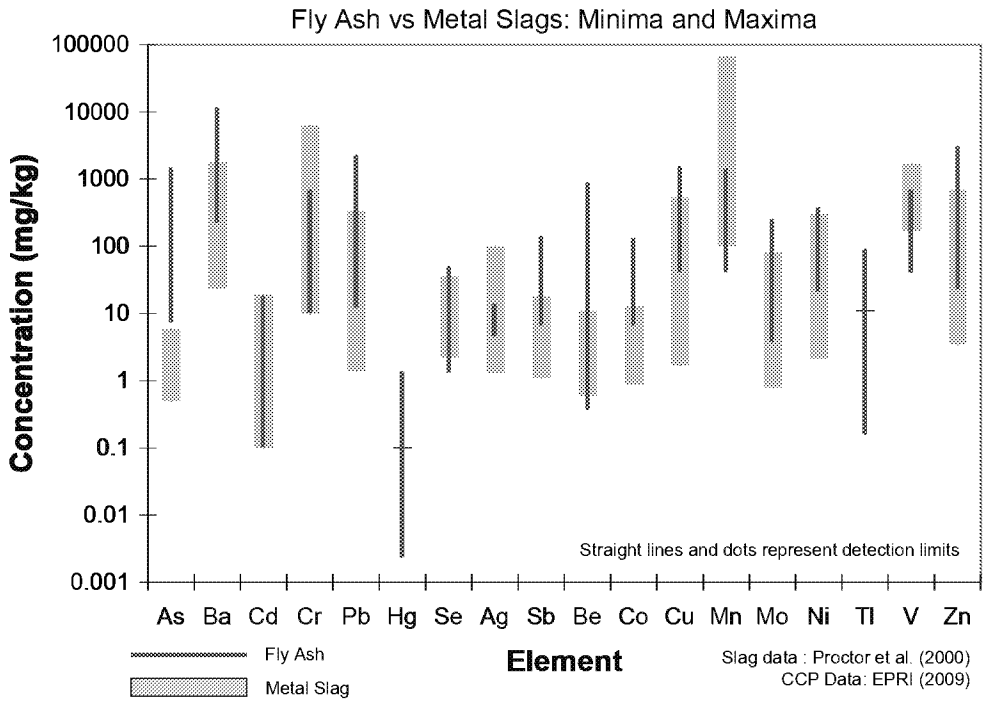

Figure 6-1
Trace element concentration ranges in metal slags and fly ash compared as minima and maxima

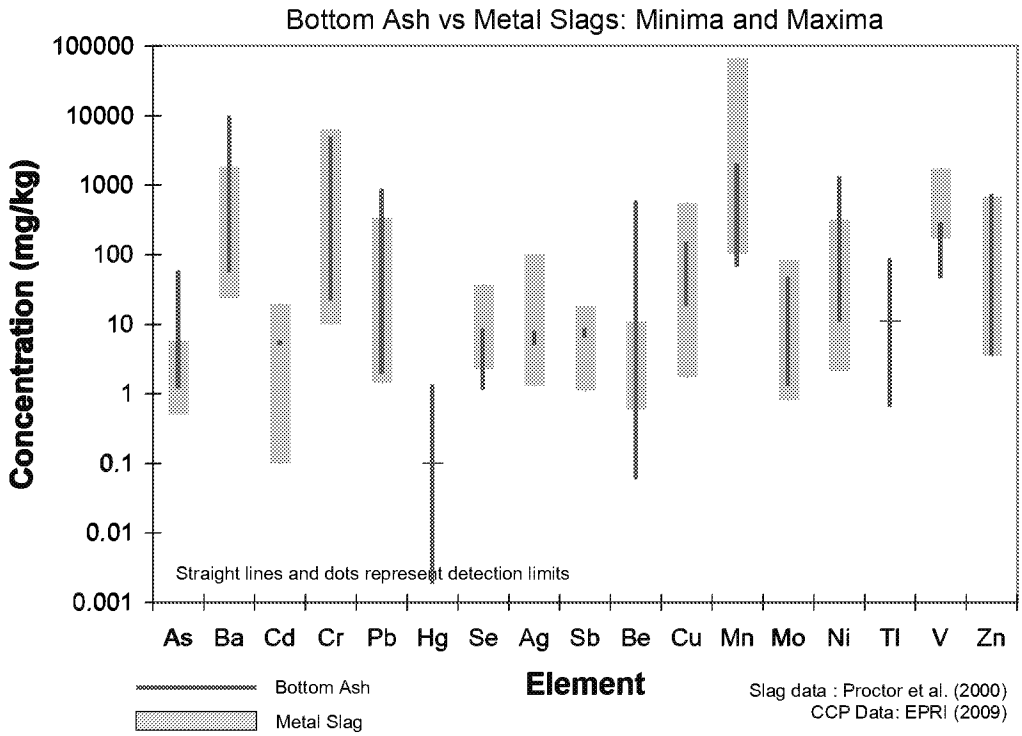

Figure 6-2
Trace element concentration ranges in metal slags and bottom ash compared as minima and maxima

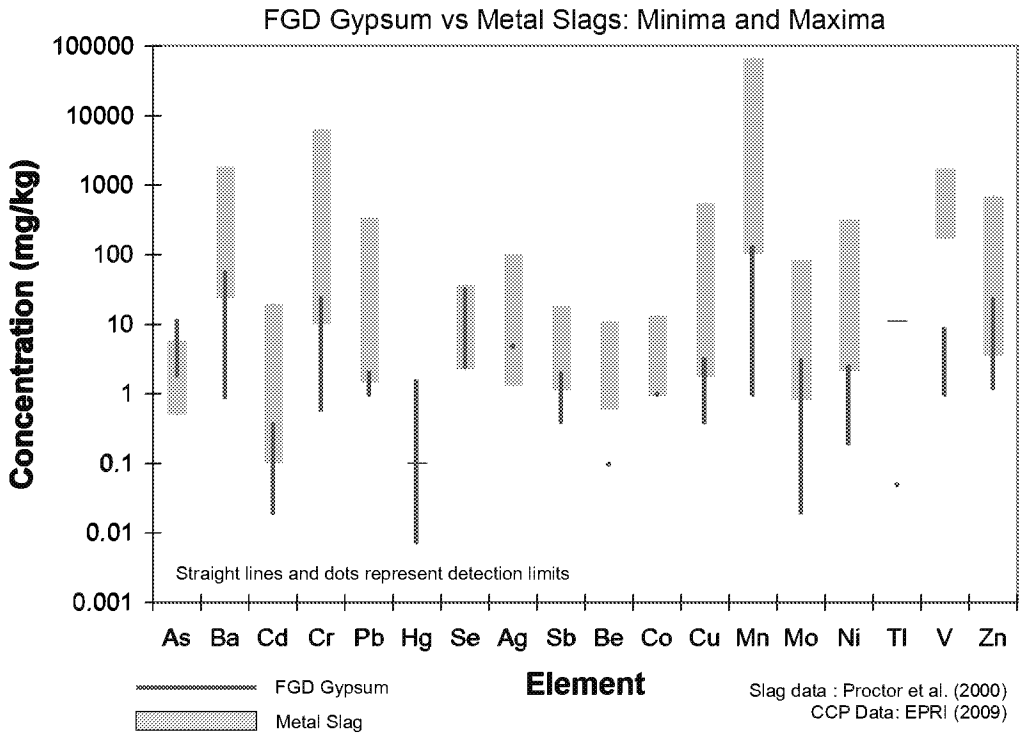

Figure 6-3
Trace element concentration ranges in metal slags and FGD gypsum compared as minima and maxima

Table 6-1
Concentration comparisons summary for CCPs and metal slags

Comparison	Fly Ash	Bottom Ash	FGD Gypsum
Above range	As		
Overlapping higher	Ba, Pb, Sb, Co, Cu, Mo, Ni, Zn	As, Ba, Pb, Ni	As
Overlapping	Se, Be	Be, Zn	
Within	Cd, Cr, Ag	Cr, Ag, Sb, Cu, Mo	Se
Overlapping lower	Mn, V	Se, Mn, V	Ba, Cd, Cr, Pb, Sb, Cu, Mn, Mo, Ni, Zn
Below range			Be, V
Unable to compare due to all non-detects	Hg, Tl	Hg, Cd, Tl	Hg, Ag, Co, Tl

Key:
CCPs
Metal Slags

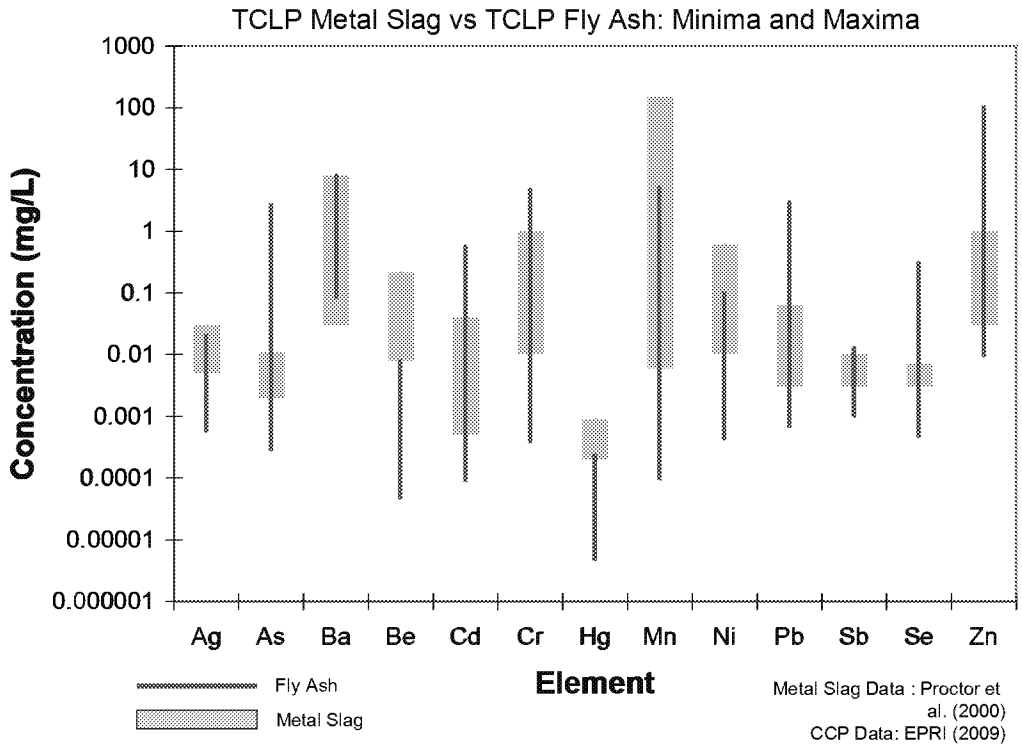

Figure 6-4
TCLP leachate concentration ranges for metal slags and fly ash

7
SPENT FOUNDRY SANDS

Information Sources

Molding sands from ferrous and non-ferrous foundries are produced by mixing silica sand with clay or organic chemical binders, most commonly bentonite clay binders. The chemical characteristics of spent foundry sands are described in great detail in the following study:

- Dungan, Robert S., and Nikki H. Dees, 2008. ***The Characterization of Total and Leachable Metals in Foundry Molding Sands***. Journal of Environmental Management, Volume 90 (2009), pp. 539-548.

This study represents the most current and comprehensive review of spent foundry sand total metals concentrations and leachate characteristics, and has been used in recent risk assessments related to spent foundry sands and their potential for beneficial reuse. The study team collected 43 waste molding sands, 74% of which were considered ferrous green sands. This percentage is believed to be representative of the industry as a whole.

Trace Element Concentration Ranges

Trace element concentration ranges of CCPs are compared to those of spent foundry sands in Figures 7-1 to 7-3. All comparisons are summarized in Table 7-1. Concentration ranges for fly ash and bottom ash are typically higher than for spent foundry sands. FGD gypsum concentration ranges are typically lower than spent foundry sand concentration ranges, with the exceptions of arsenic and boron.

TCLP and SPLP leaching data are plotted in Figures 7-4 and 7-5. For TCLP, the ranges for barium, cadmium, chromium, and lead for fly ash overlap those for foundry sand, but the ranges are much larger for fly ash. The fly ash ranges for silver, antimony, beryllium, copper, and nickel are all completely below the ranges for foundry sands. For SPLP, the fly ash ranges are typically comparable to or below ranges for foundry sands, with the exception of arsenic, chromium, and barium.

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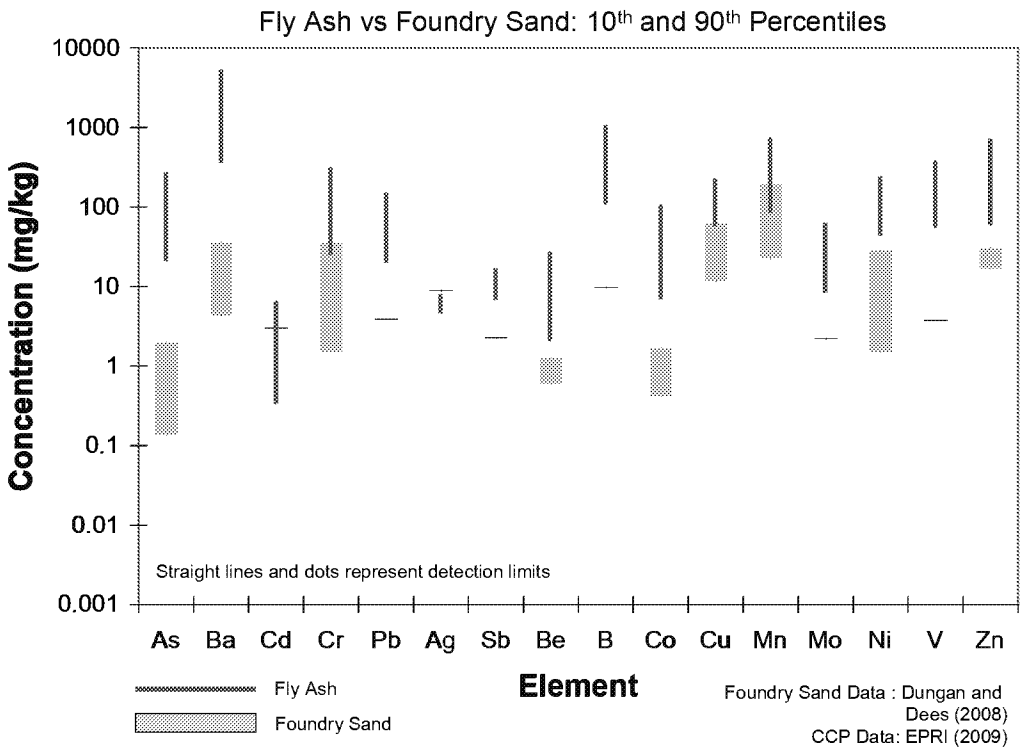

Figure 7-1
Trace element concentration ranges for spent foundry sand and fly ash

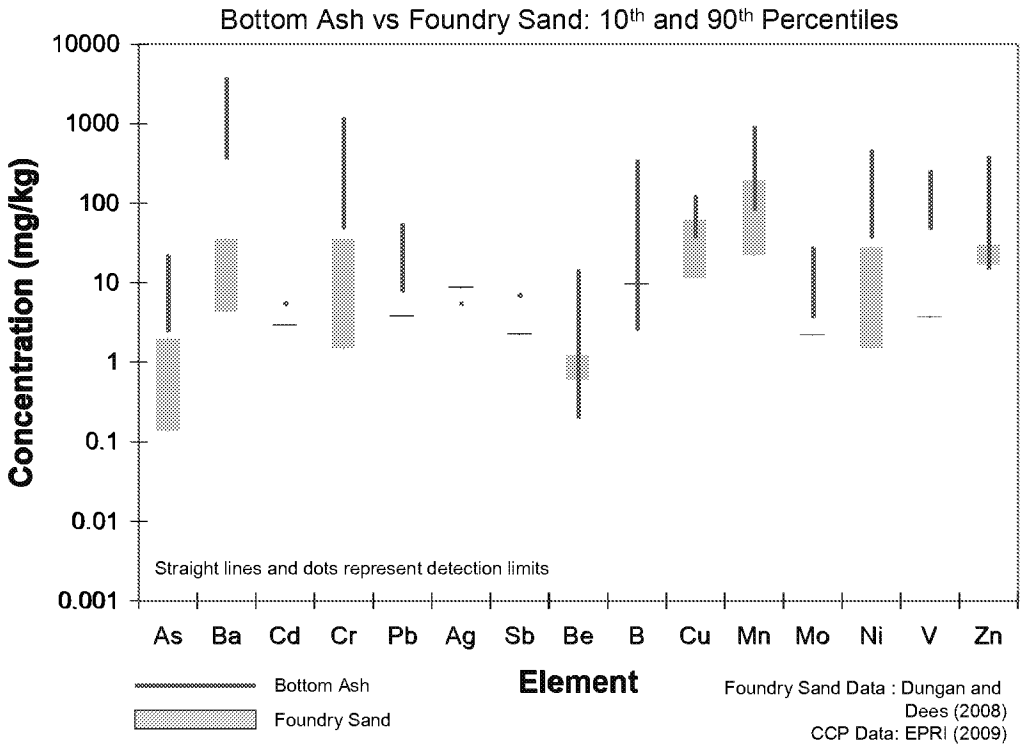

Figure 7-2
Trace element concentration ranges for spent foundry sand and bottom ash

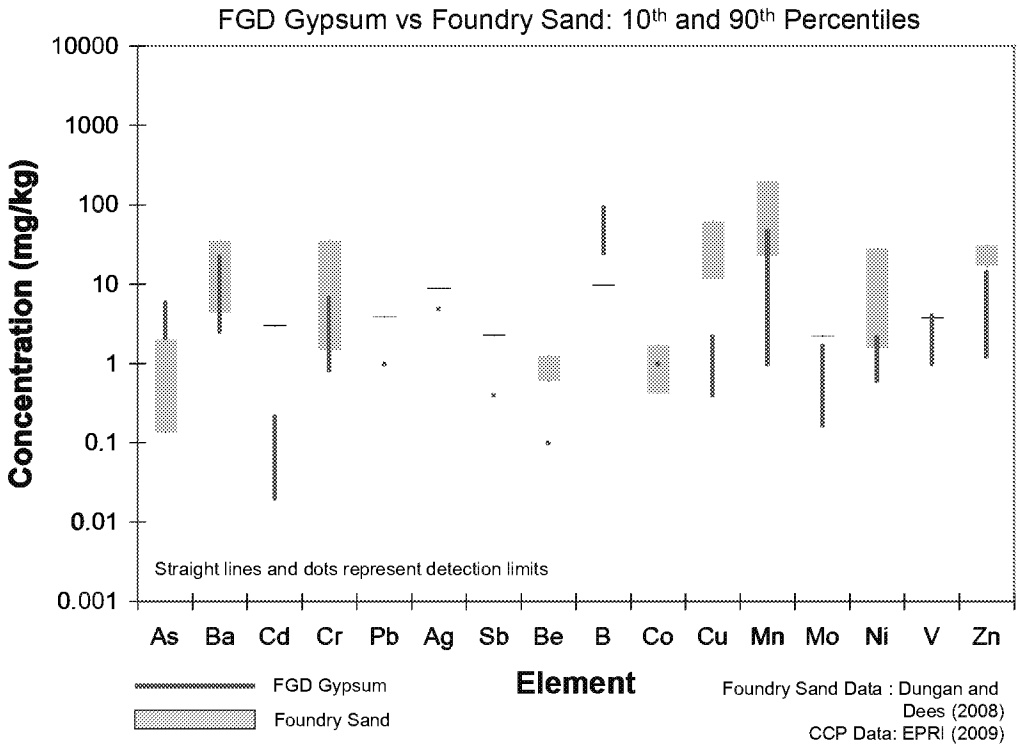

Figure 7-3
Trace element concentration ranges for spent foundry sand and FGD gypsum

Table 7-1
Concentration comparisons summary for CCPs and spent foundry sands

Comparison	Fly Ash	Bottom Ash	FGD Gypsum
Above range	As, Ba, Pb, Sb, Be, B, Co, Mo, Ni, V, Zn	As, Ba, Cr, Pb, Mo, Ni, V	As, B
Overlapping higher	Cr, Cu, Mn	Cu, Mn	
Overlapping		Be, Zn	
Within			
Overlapping lower			Ba, Cr, Mn, Ni
Below range			Be, Cu, Zn
Unable to compare due to all non-detects	Cd, Ag	Cd, Ag, Sb, B	Cd, Pb, Ag, Sb, Co, Mo, V

Key:
CCPs
Spent Foundry Sands

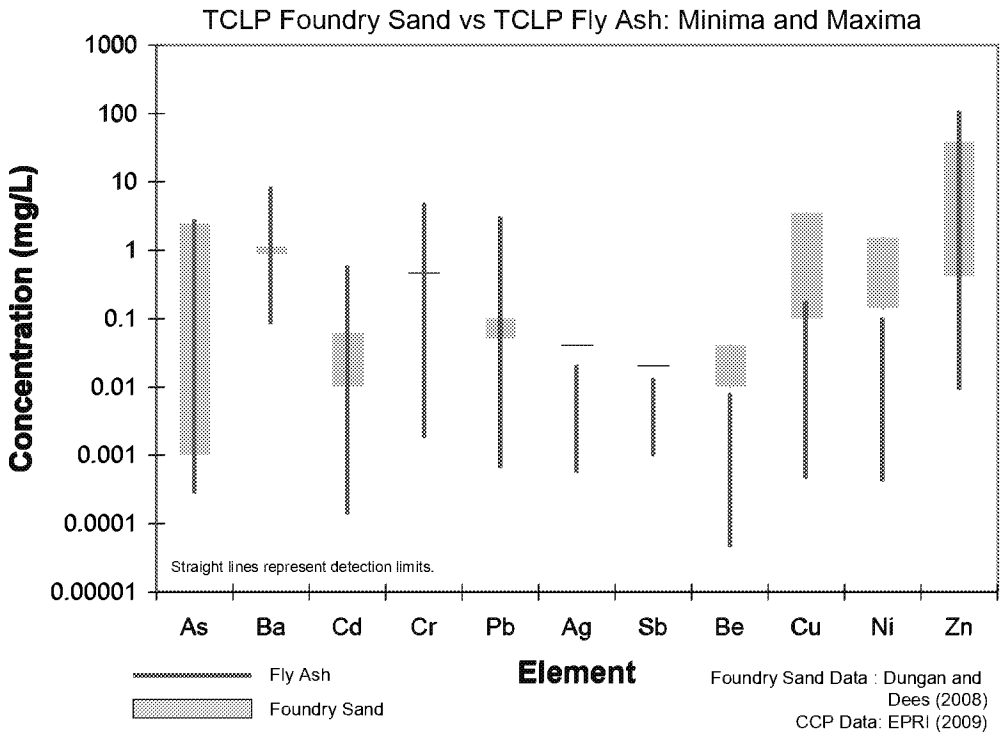

Figure 7-4
TCLP leachate concentration ranges for spent foundry sand and fly ash

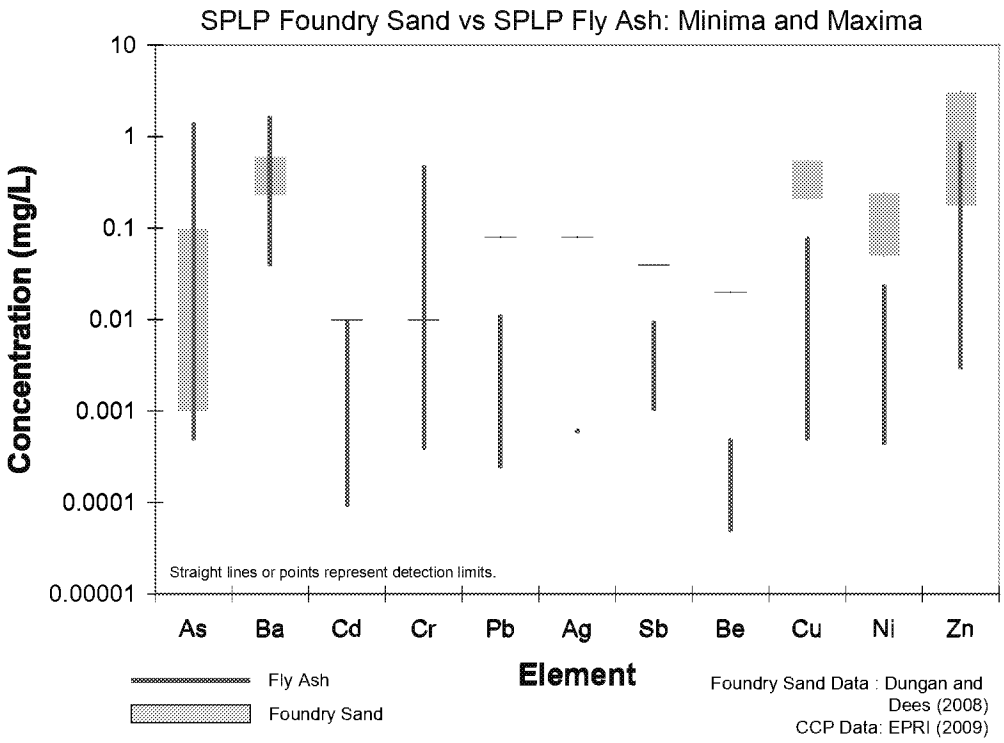

Figure 7-5
SPLP leachate concentration ranges for spent foundry sand and fly ash

8
BIOSOLIDS

Information Sources

Biosolids are the nutrient-rich organic materials resulting from the treatment of sewage sludge, and are often beneficially used as fertilizers and soil amendments. The U.S. Environmental Protection Agency recently completed a review of treated sewage sludge (biosolids) characteristics. The results of the survey are presented in the following report:

- U.S. Environmental Protection Agency, 2009. ***Targeted National Sewage Sludge Survey Statistical Analysis Report***. EPA-822-R-08-018.

The survey collected samples from 74 randomly selected publicly owned treatment works in 35 states, analyzing for 145 analytes, including 28 metals. The survey is the most comprehensive and reliable dataset produced to date for use in the current study.

Trace Element Concentration Ranges

Trace element concentration ranges of CCPs are compared to those of biosolids in Figures 8-1 to 8-3. All comparisons are summarized in Table 8-1. Concentration ranges for fly ash and bottom ash are generally comparable to or higher than the ranges for biosolids. FGD gypsum concentration ranges are typically lower than the ranges for biosolids.

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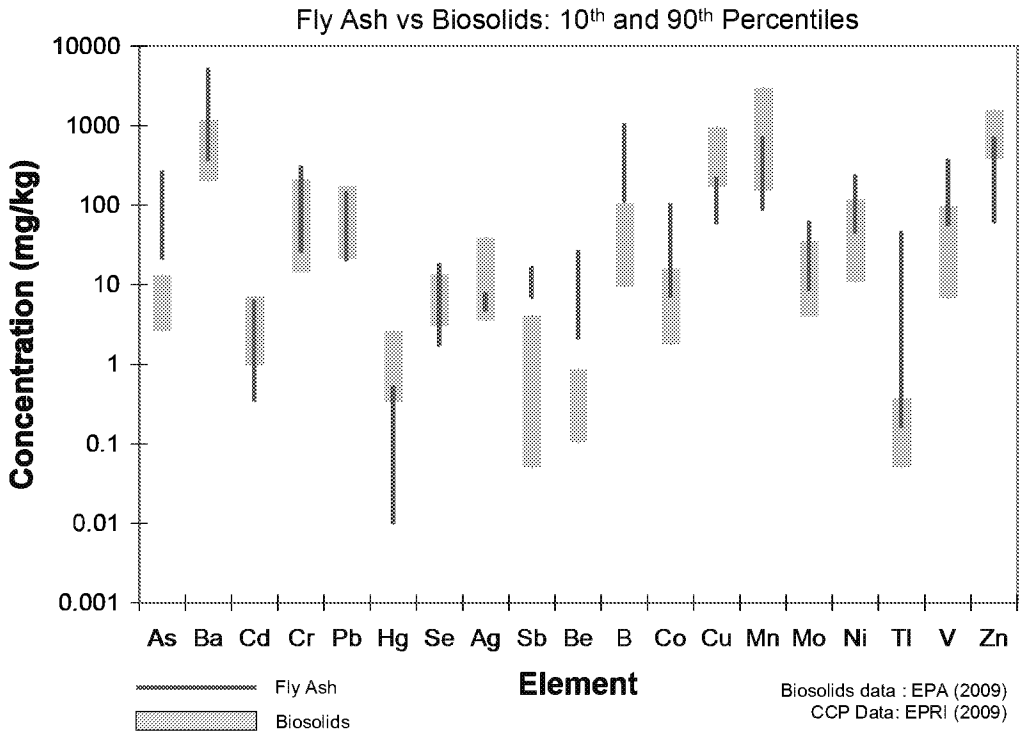

Figure 8-1
Trace element concentration ranges for biosolids and fly ash

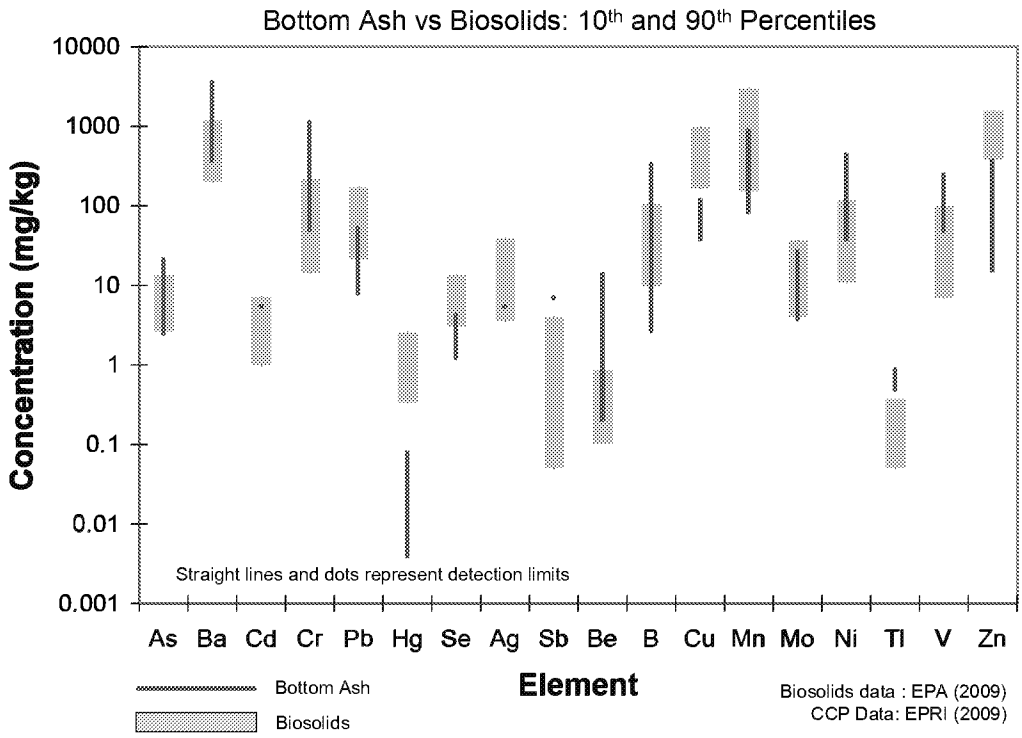

Figure 8-2
Trace element concentration ranges for biosolids and bottom ash

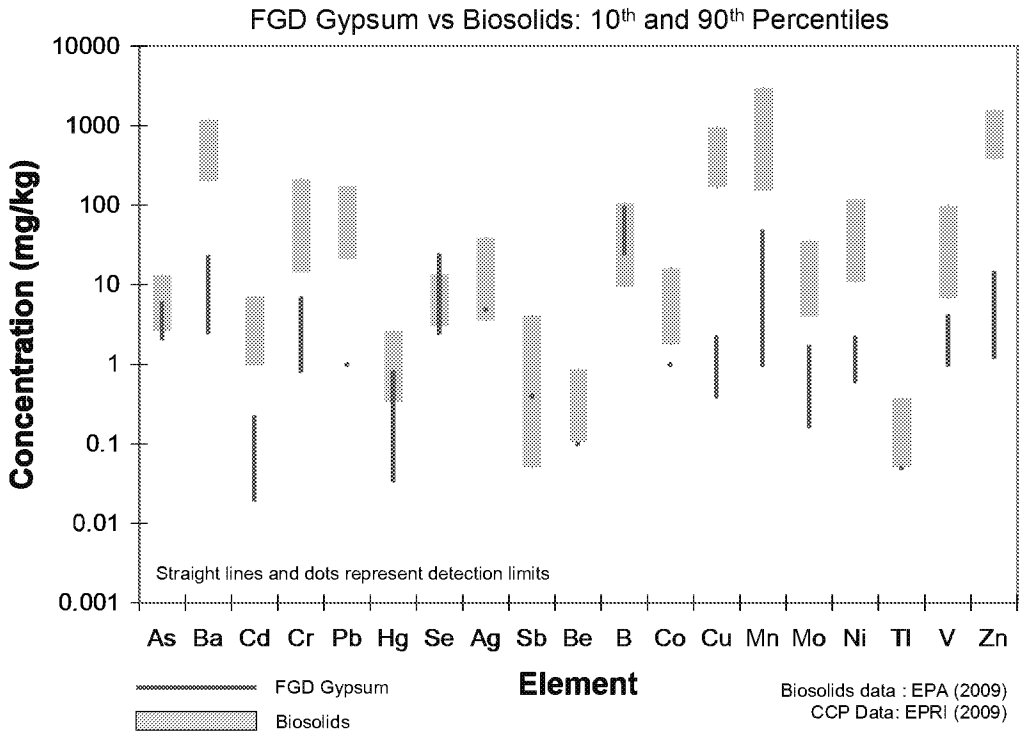

Figure 8-3
Trace element concentration ranges for biosolids and FGD gypsum

Table 8-1
Concentration comparisons summary for CCPs and biosolids

Comparison	Fly Ash	Bottom Ash	FGD Gypsum
Above range	As, Sb, Be, B	Tl	
Overlapping higher	Ba, Cr, Co, Mo, Ni, Tl, V	Ba, Cr, Be, Ni, V	
Overlapping	Se	As, B	Se
Within	Ag		B
Overlapping lower	Cd, Pb, Hg, Cu, Mn, Zn	Pb, Se, Mn, Mo	As, Hg
Below range		Hg, Cu, Zn	Ba, Cd, Cr, Pb, Be, Co, Cu, Mn, Mo, Ni, Tl, V, Zn
Unable to compare due to all non-detects		Cd, Ag, Sb	Ag, Sb

Key:
CCPs
Biosolids

9
REGULATORY LEVELS

Toxicity Characteristic Leaching Procedure

CCPs did not exceed any hazardous limits in TCLP test data from EPRI studies (Figure 9-1). Out of 64 samples from 50 different power plant sites identified in EPRI databases, no TCLP result for CCPs exceeded the TCLP hazardous waste limits. These data are consistent with EPA data from the previous regulatory determinations indicating very few hazardous waste limit exceedances using the RCRA criteria.

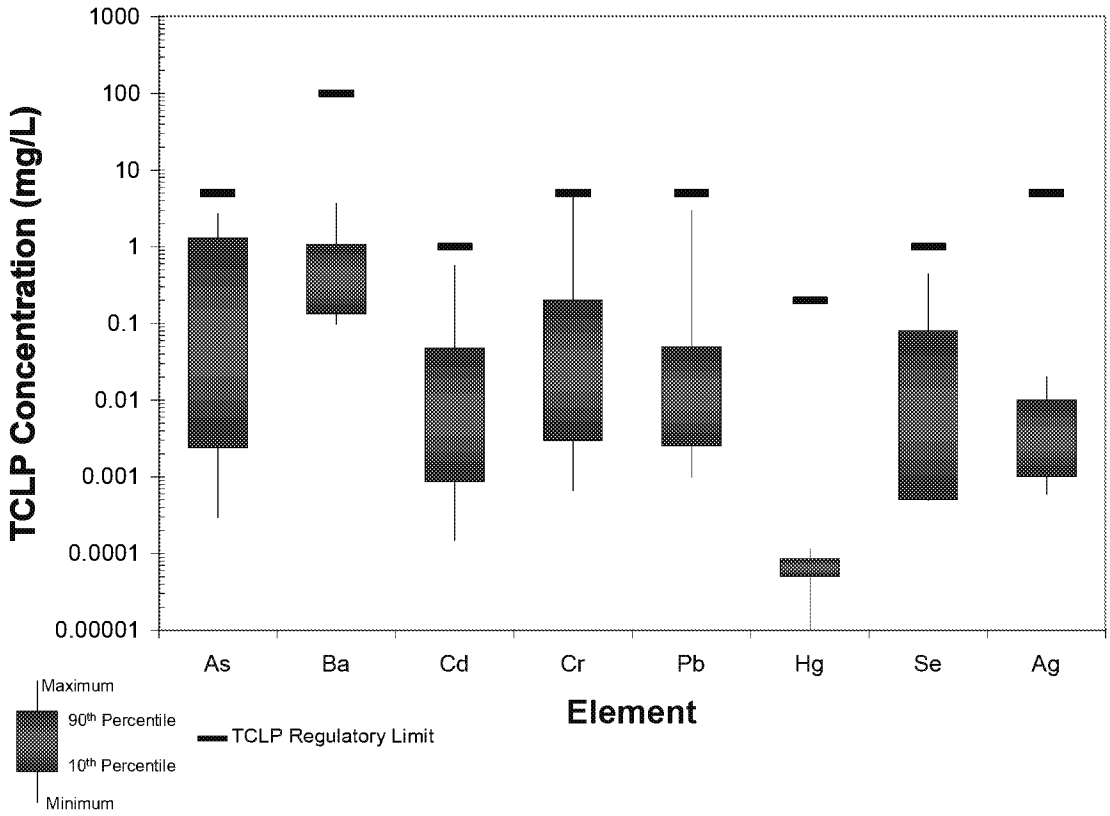

Figure 9-1
Coal ash TCLP leachate concentration ranges compared to regulatory limits

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EPA Residential and Industrial Soil Screening Levels

Concentration ranges of fly ash, bottom ash, and FGD gypsum are compared to EPA's residential soil screening levels (RSLs) for ingestion and dermal exposure in Figures 9-2, 9-3, and 9-4. Most trace element concentration concentrations fall below the RSLs for all three materials, with the exception of arsenic. Materials other than coal ash and gypsum, including uncontaminated soil, also typically exceed the RSL as well as the industrial soil screening level (ISL) for arsenic (Figure 9-5).

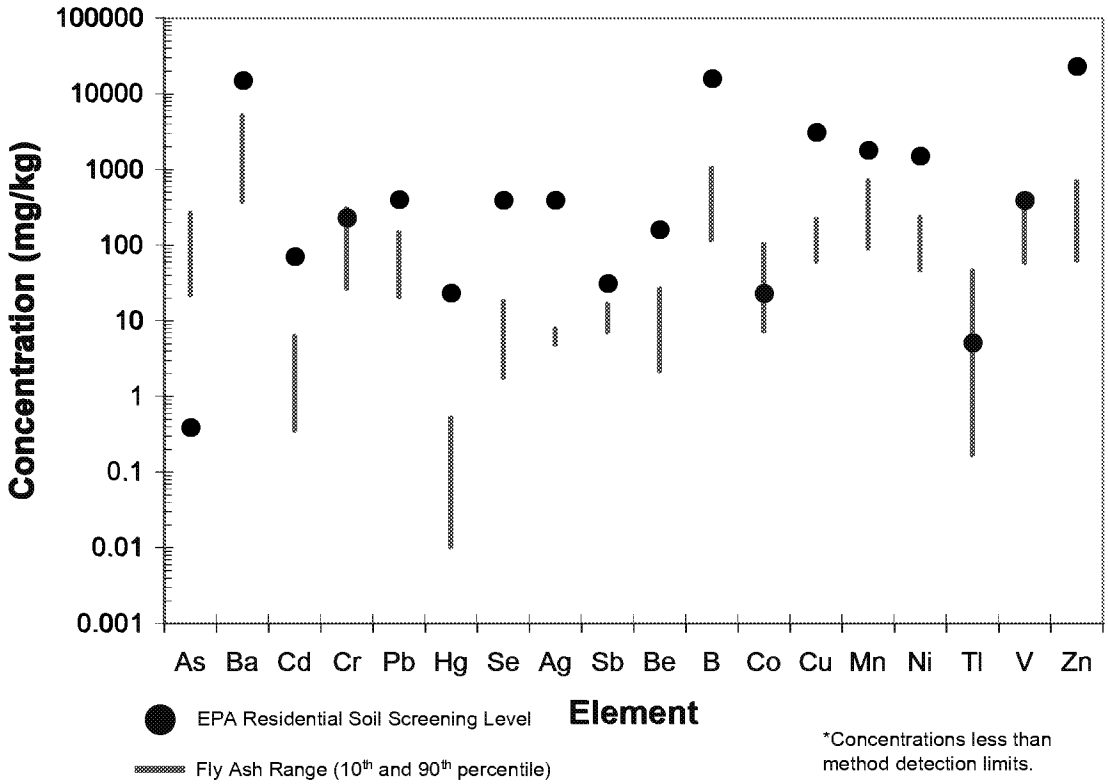

Figure 9-2
Trace element concentration ranges in fly ash compared to EPA residential soil screening levels

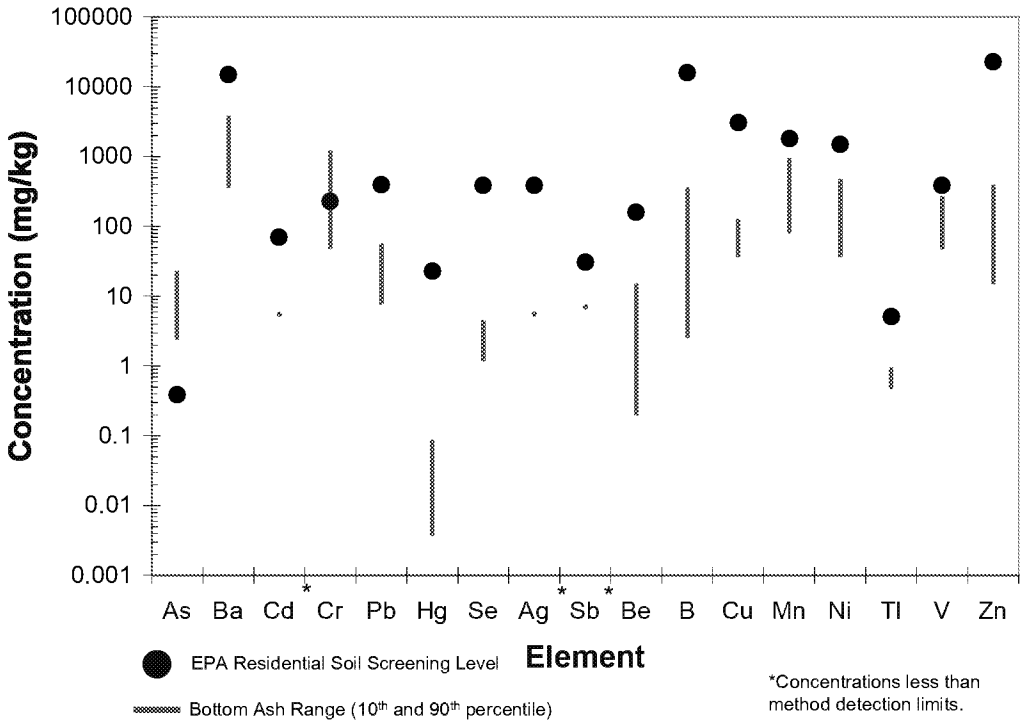

Figure 9-3
Trace element concentration ranges in bottom ash compared to EPA residential soil screening levels

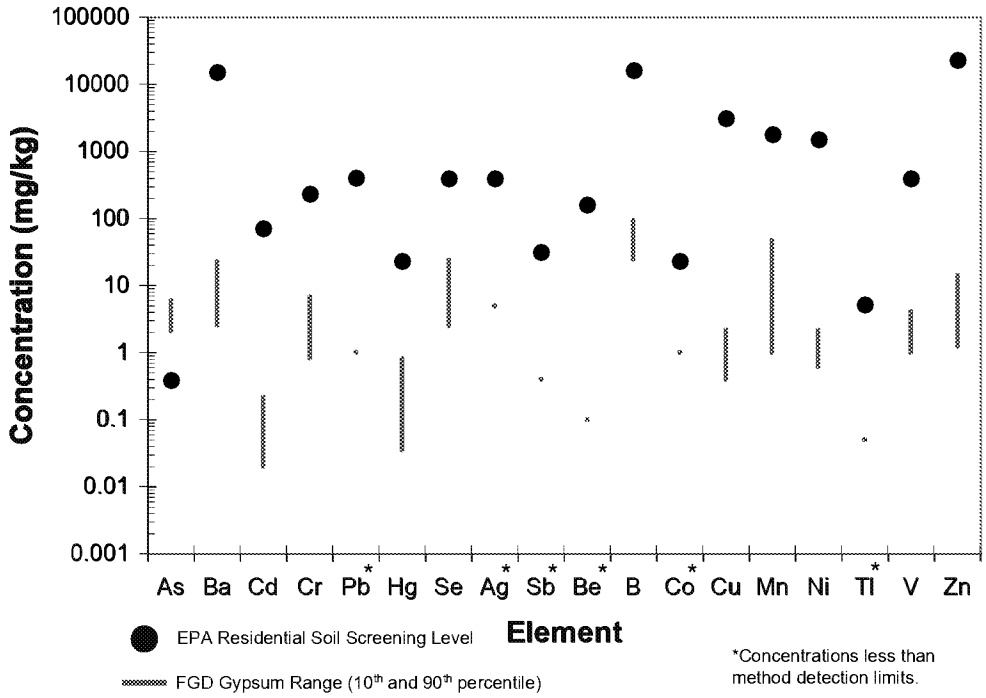

Figure 9-4
Trace element concentration ranges in FGD gypsum compared to EPA residential soil screening levels

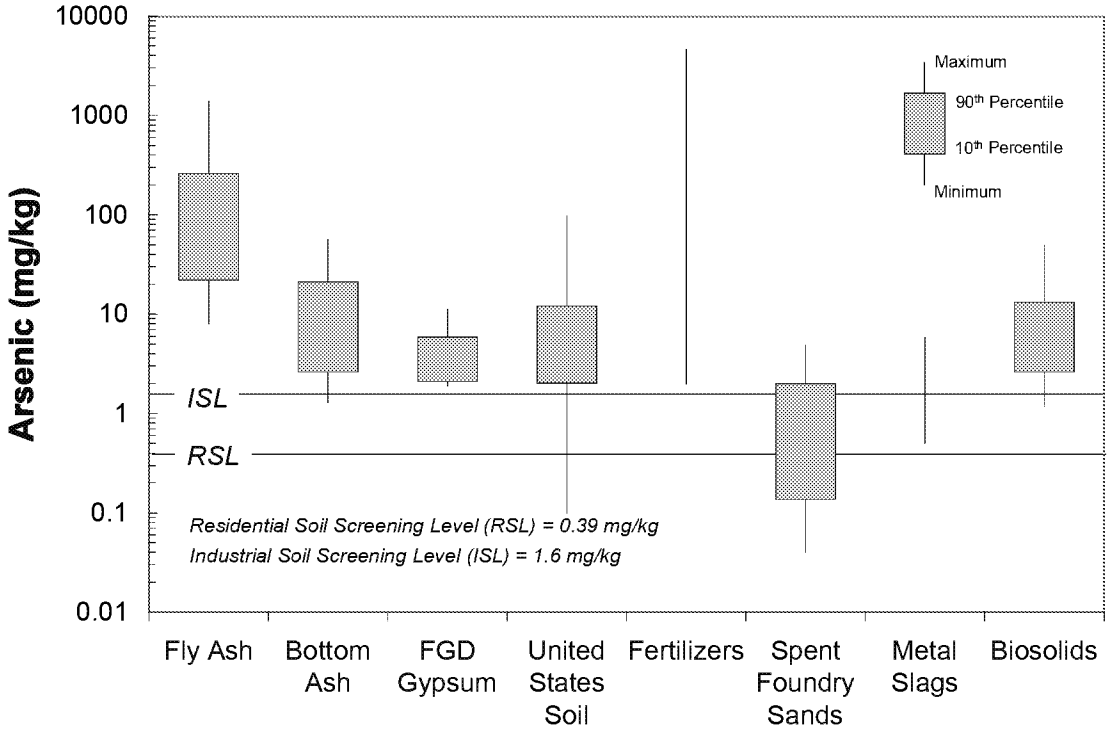

Figure 9-5
Comparison of CCP, soil, fertilizer, spent foundry sand, metal slag, and biosolid arsenic concentrations to EPA residential and industrial soil screening levels

10
SUMMARY

This report compared chemical characteristics of CCPs to chemical characteristics of common natural and manufactured materials, including rock, soil, fertilizer, metal slag, spent foundry sands, and biosolids. A literature review was performed to identify data that were current, representative, and credible. Both major chemistry and trace element chemistry of the CCPs were compared to the chemistry of the six other materials.

- The overall major chemical composition of both bottom ash and fly ash is similar to that of siliceous rocks, particularly shale. Oxides of silicon, aluminum, iron, and calcium make up more than 90% of most siliceous rocks, soils, fly ash, and bottom ash. Trace elements make up less than 1% of all of these materials.
- Trace element ranges for fly ash were typically higher than the ranges for soil, rock, and foundry sand, and comparable to or sometimes higher than the ranges for fertilizer, metal slags, and biosolids.
- Trace element ranges for bottom ash were typically higher than the ranges for soil and foundry sands, comparable to or sometimes higher than the ranges for rocks, fertilizer, and biosolids, and comparable to the ranges for metal slags.
- FGD gypsum is very similar chemically to mined rock gypsum. Both are composed almost exclusively of hydrated calcium sulfate. With a few exceptions, trace element ranges for FGD gypsum were generally comparable to or lower than the ranges for rocks and fertilizers, and lower than the ranges for soils, metal slags, foundry sands, and biosolids.
- Concentration ranges of trace constituents in fly ash, bottom ash, and FGD gypsum typically fall below the EPA residential and industrial soil screening levels for ingestion and dermal exposure, with the exception of arsenic. Many materials, including uncontaminated soils and other beneficially used materials, also commonly exceed the RSL and ISL for arsenic.
- CCPs did not exceed any hazardous limits in TCLP test data from EPRI studies. Out of 64 samples from 50 different power plant sites identified in EPRI databases, no TCLP result for CCPs exceeded the TCLP hazardous waste limits. These data are consistent with EPA data from the previous regulatory determinations, indicating very few hazardous waste limit exceedances using the RCRA criteria.

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ELECTRIC POWER RESEARCH INSTITUTE

Composition and Leaching of FGD Gypsum and Mined Gypsum

2011 TECHNICAL REPORT

Composition and Leaching of FGD Gypsum and Mined Gypsum

1022146

Final Report, November 2011

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ABSTRACT

Flue gas desulfurization (FGD) equipment on new and existing coal-fired power plants controls sulfur dioxide (SO2) emissions, and produces a solid that is removed in either slurry or dry form. EPRI sponsored an investigation to characterize FGD gypsum—the solid produced by wet FGD systems with forced air oxidation—from a representative sampling of U.S. power plants. A single contractor collected 32 samples from 29 power plants in 13 states. In addition, 11 natural gypsum samples from mines in the United States, Mexico, and Canada were collected for comparison purposes. The samples were analyzed for gypsum purity, total composition, toxicity characteristic leaching procedure (TCLP) leachate concentrations, and synthetic precipitation leaching procedure (SPLP) leachate concentrations. A single laboratory performed each aspect of the analysis. These procedures yielded a highly consistent dataset that was not confounded by sample collection or interlaboratory variability.

Analytical results for FGD gypsum samples were compared to determine if operation processes significantly affected total or leachable concentrations. The most pronounced effect was noted for washed samples, which had lower solid and leachable concentrations than unwashed samples for many of the elements analyzed. The total composition of the FGD gypsum was greater than 90% calcium sulfate dihydrate (CaSO4•2H2O). Concentrations for other elements were all less than 0.1%. The FGD gypsum purity ranged from 90% to 99%; mined gypsum purity ranged from 66% to 98%.

TCLP leachate concentrations were all well below the respective toxicity characteristic (TC) limits for defining a hazardous waste. Comparison of SPLP leachate extracts found that FGD gypsum leachate concentrations were similar to or lower than mined gypsum for two-thirds of the elements analyzed. FGD gypsum is substituted directly for mined gypsum in manufactured products such as wallboard and in agricultural applications. The constituents in the FGD gypsum SPLP extracts with the highest concentrations relative to the mined gypsum extracts were boron, mercury, and selenium, although the median concentrations of these constituents were relatively low.

Keywords
FGD Gypsum
Mined Gypsum
FGD Gypsum Composition
Leachate
TCLP
Purity

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1
INTRODUCTION

Power companies are increasingly installing flue gas desulfurization (FGD) equipment on new and existing coal-fired power plants to control sulfur dioxide (SO_2) emissions. FGD systems typically consist of introduction of an alkaline reagent in an absorber vessel; the reagent reacts with the SO_2 in the flue gas to produce a solid that is removed in either a slurry or dry form. These FGD solids are then either used in manufacturing, geotechnical, or agricultural applications, or are disposed of in landfills or ponds.

The solids produced depend on the type of FGD system. The focus in this report is on FGD gypsum, which is produced by wet systems using a lime or limestone reagent and employing forced oxidation (LSFO). These units typically produce a relatively pure gypsum product. Other systems may produce calcium sulfite or sodium-sulfur compounds, and may include entrained fly ash. FGD systems and the solids produced are described in more detail in Section 2.

Purpose

The purpose of this report is to provide characterization data for FGD gypsum from a representative sampling of power plants across the U.S. The data include total composition, purity, and leaching characteristics. Because FGD gypsum is substituted directly for mined gypsum in manufactured products such as wallboard and in agricultural applications, characterization data for mined gypsum from a broad cross-section of gypsum mine locations are also provided for comparison.

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FGD GYPSUM PRODUCTION AND MANAGEMENT

FGD Technologies

There are a variety of FGD systems for controlling SO_2 emissions at power plants in the US. Because these systems produce solids with different physical and chemical characteristics, it is important to understand the basic processes and how they differ. These differences can significantly affect how the materials are handled, disposed of, or utilized.

FGD systems can generally be categorized as "wet" or "dry." In wet FGD systems, an aqueous slurry or solution containing the reagent, usually slaked lime or finely ground limestone, along with recirculated reaction products, is sprayed into the absorber and contacts the flue gas. The calcium in the reagent reacts with the sulfur in the flue gas to produce calcium sulfite. The solid produced collects as a slurry in the reaction tank at the bottom of the absorber. Intermittently, a portion of the recirculating slurry is withdrawn and dewatered to remove solids from the slurry. In systems using *inhibited oxidation*, the solid product is primarily calcium sulfite hemihydrate ($CaSO_3 \bullet \frac{1}{2}H_2O$), in a slurry form that is generally about 5% solids content. Calcium sulfite hemihydrate is difficult to dewater and handle as a solid, so it is often mixed with fly ash and lime prior to disposal or reuse to create a more stable material for handling. This mixed product, often called fixated scrubber sludge (FSS) has limited uses and is usually disposed. In systems using *forced oxidation*, the solid product is calcium sulfate dihydrate (gypsum, $CaSO_4 \bullet 2H_2O$), which is more easily dewatered and handled. Most FGD gypsum is used, primarily as a direct replacement for mined gypsum in manufactured products (e.g., wallboard) and agricultural applications. *Natural oxidation* systems produce a mixture of the two compounds that varies in percentage by power plant. With the exception of a few older systems, generating units with wet FGD systems capture fly ash separately in electrostatic precipitators (ESPs) or fabric filter baghouses located in front of the FGD absorber.

Dry FGD systems produce a solid that does not require dewatering, and include spray dryer absorbers (SDAs) and furnace or duct injection systems. SDAs are sometimes referred to as semi-wet because a reagent slurry, typically slaked lime, is injected into the absorber and atomized, and the water is evaporated, resulting in collection of a dry Ca-S product. The reaction product is primarily calcium sulfite hemihydrate, along with some unreacted lime. The SDA product is generally collected in a downstream baghouse. Most spray dryers in the U.S. also capture fly ash with the SDA product, resulting in a mixture of the two. Some newer units in the U.S. collect fly ash prior to the spray dryer absorber to preserve use options for the fly ash; in some cases the fly ash and SDA product are then often mixed prior to disposal. Furnace and duct injection are true dry FGD systems that inject dry powdered calcium- or sodium-based reagents into the furnace or duct prior to the ESP or baghouse. The FGD product (calcium or sodium sulfite/sulfate and unreacted sorbent) is then captured with the fly ash. There are several variations on the dry FGD technologies, such as circulating fluidized beds.

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FGD Gypsum

Quantities

As described above, the term FGD gypsum refers specifically to products that are nearly pure $CaSO_4 \bullet 2H_2O$, produced primarily in wet LSFO scrubbers. In addition, some high natural oxidation scrubbers can produce a relatively pure gypsum product without the need to employ forced oxidation. With the exception of a few older facilities, LSFO absorbers are located downstream of the ESP or baghouse used for capturing fly ash, and therefore the gypsum produced has a low fly ash content (typically <1%). FGD products that consist of a large percentage of calcium sulfite, or contain a large percentage of fly ash, are not included in the definition of FGD gypsum for purposes of this report.

FGD gypsum is the most common FGD solid produced, accounting for 18 million short tons in 2009 (ACAA, 2011). This volume could double over the next decade as more generating units add FGD control technology in response to new requirements for air emissions controls (EPRI, 2006a).

Dewatering

FGD gypsum is initially collected in the absorber in slurry form with low solids content (~5%) that requires dewatering prior to management. Dewatering can be accomplished by either mechanical systems or gravity drainage. Mechanical dewatering systems generally have hydrocyclones for primary dewatering, and centrifuges, vacuum drums, or vacuum belt filters for secondary dewatering. Water from the primary and secondary dewatering systems is reclaimed and returned to the FGD process, or blown-down to the wastewater treatment system. A typical mechanical system for dewatering FGD gypsum is shown in Figure 2-1. Mechanical systems can dewater FGD gypsum to produce a moist (7 to 12% moisture) but free-flowing solid that is easily handled.

Mechanical systems often include a water spray wash as part of the secondary dewatering in order to lower chlorides to meet specifications for use in wallboard. The spray removes soluble chloride, and may remove ammonia, fine particles, and some trace constituents.

As an alternative to mechanical dewatering, FGD gypsum may be “stacked” and free moisture allowed to gravity drain. Systems that use a gypsum stack typically do not have primary or secondary dewatering. Instead they sluice gypsum slurry from the absorber to a ponded area. As the solids settle from the slurry, they are dredged and placed in a pile to allow free moisture to drain by gravity, often in what is known as a rim ditch stack. Gravity drainage systems can dewater FGD gypsum to about 15 to 25% free moisture content. Sluice and drainage water are either reclaimed and returned to the FGD process, or are treated and discharged. In some cases, rather than dredging, the area is managed so that with time, the settled gypsum level rises above grade, producing a stack of settled gypsum solids.

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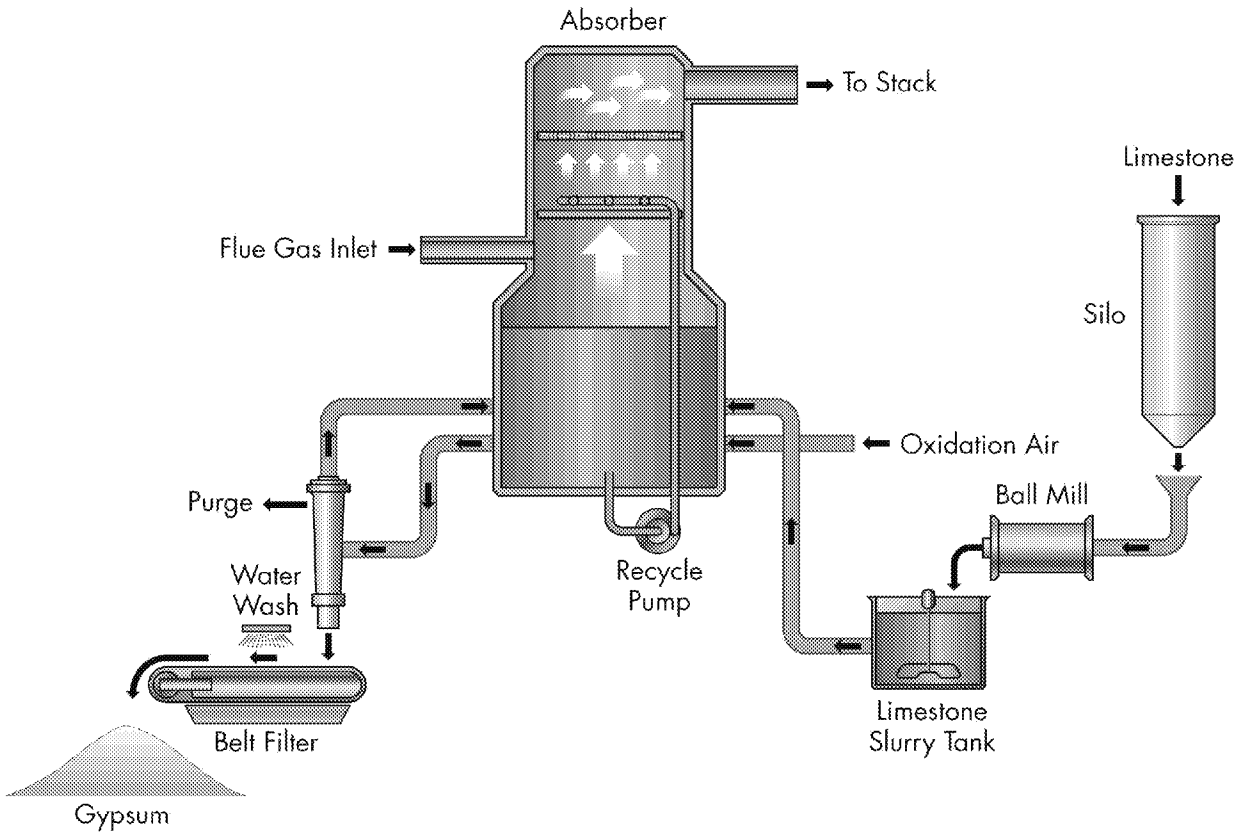

Figure 2-1
Typical dewatering system for forced oxidation wet FGD

Use

FGD gypsum is a high-value product that is most often used as a direct replacement for mined gypsum feedstock for wallboard production, or less commonly as an additive to cement and concrete, and as an agricultural soil amendment. In 2009, nearly 9 million short tons were used in the United States, primarily (81%) as feedstock for wallboard manufacture (ACAA, 2011). The rate of FGD gypsum use in 2009 was down from previous years, reflecting the increased production of FGD gypsum, as well as the downturn in the housing market.

FGD gypsum used for wallboard production typically has relatively strict product specifications imposed by the wallboard manufacturers (EPRI, 2006a). Specifications include free moisture content, gypsum purity, particle size distribution, maximum combustibles, chloride, total soluble salt, and/or ammonia content. Washing is often required during the secondary dewatering step to meet chloride and ammonia specifications.

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A growing use for both mined and FGD gypsum is in agricultural applications. In addition to improving crop yield, gypsum application can allow farming on otherwise marginal soils, and can lead to decreased use of fertilizers due to improved infiltration and less runoff. Documented benefits include (EPRI, 2008):

- Ameliorating subsoil acidity, allowing greater root penetration
- Providing a source of plant nutrients (calcium, sulfur)
- Improving soil physical properties by promoting aggregation
- Improving infiltration on poorly drained soils
- Reducing loss of phosphorus and nitrogen in runoff
- Remediating sodic soils
- Facilitating no-till practices on clay soils

In 2009, about 282,000 short tons of FGD gypsum were used in agricultural applications (ACAA, 2011). A large body of research at EPRI and elsewhere is currently underway to document the agricultural benefits of FGD gypsum, define appropriate application rates for various crops and soils, and evaluate the potential risks to crops, soil, water, and biota (EPRI, 2006b, 2008, 2011a, 2011b).

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3
MATERIALS AND METHODS

FGD Gypsum Sampling

A total of 32 FGD gypsum samples were collected from 29 power plants as part of this project. States where samples were collected are shown in Figure 3-1. All sampling for this project was coordinated by Natural Resource Technology (NRT) using the standardized procedures described below.

Figure 3-1
States where FGD gypsum and mined gypsum samples were collected

General Sample Handling

FGD gypsum sampling points, as described later in this section, were identified for each plant. Sampling personnel collected bulk FGD gypsum samples from each sampling point. Sample aliquots were split from the bulk sample as described below.

Samples were collected in new, clean 5-gallon metal or plastic buckets with sealable lids. Prior to sample collection, buckets and implements used to collect samples (trowels, shovels, etc.)

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were "rinsed" three times with gypsum from the sample site by filling and then emptying the bucket.

New disposable gloves were worn each time a different location was sampled, and gloves were donned immediately prior to sampling. Each sample was clearly labeled with the sample number, plant code, date and time collected, and the initials of the personnel collecting the sample. All samples were handled under chain of custody procedures and shipped to the laboratories via ground transport.

Sample Collection

For units with mechanical dewatering systems, the preferred sampling point was the conveyor between the dewatering device and the gypsum processing area; however, alternative sample points were used when the conveyor was unavailable or could not be safely sampled. Sample collection points are described below.

Drum Filter

FGD gypsum sampled from the drum filter was skimmed off the filter, as it rotated, using a shovel or hand trowel, and placed directly into the 5-gallon pails. The sample was taken from multiple points covering the length of the filter. The material was then composited as described under Sample Processing.

Conveyor from Mechanical Dewatering Device (Vacuum Belt/Drum Filter)

FGD gypsum sampled from the conveyor on the outlet side of the vacuum belt or drum filter was collected using a shovel or trowel to remove material from the conveyor and placed directly onto a processing mat or into 5-gallon pails. This procedure was repeated until there was sufficient material to obtain the bulk sample volume. The material was then composited as described under Sample Processing.

Dry Gypsum or Rim Ditch Stacks

FGD gypsum stack samples were collected from several locations around the stack. If a crust was present, a shovel was used to dig beneath the crust so that fresh gypsum was exposed. At each sample point on the stack, a shovel was used to partially fill each 5-gallon bucket with sample. This process was repeated until the bulk sample volume was obtained. The material was then composited as described under Sample Processing.

Impoundment

One sample (228) was collected from an impoundment where it had been sluiced. The gypsum was very hard and a shovel could not penetrate more than one or two inches into the material. Therefore, the sample was collected by scraping surficial gypsum at several points across the impoundment.

Sample Processing

After collection and prior to shipment to the analytical laboratories, bulk samples were homogenized so that each laboratory received samples of similar composition. Samples were

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composited by spreading a new Visqueen® (or equivalent) processing mat flat on the ground surface in a location protected from precipitation and blowing dust. The entire bulk sample was placed onto the mat and the material was homogenized using a shovel and then placed into 5-gallon buckets. The buckets were then sealed, and the lids secured with packaging tape. Aliquots were taken from the homogenized buckets and submitted to each laboratory.

Sample Nomenclature and Labeling

Each sample was identified by a unique 3-digit sample ID assigned consecutively from an EPRI sample database. Each power plant was assigned a unique 5-digit Plant ID. Each sample was clearly labeled with the Sample ID, Plant ID, date and time collected, and the initials of the personnel collecting the sample. The EPRI sample database also contains additional information such as which unit(s) the sample was collected from; bulk sample volume; sample location; washed vs. unwashed; and date of sample homogenization. If follow-up sampling was provided at a particular plant, then the follow-up samples received a new unique sample ID.

Site-Specific Sample Collection Information

Site-specific sample collection information is summarized in Table 3-1, and detailed information is provided in Appendix A. Included are basic information about how the gypsum was processed after leaving the absorber, and the sample collection method. Note that some samples were collected from a fresh pile beneath the conveyor belt; these samples were considered "off-belt" because they were freshly placed. Figures 3-2 through 3-4 show examples of sampling locations.

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Table 3-1
Summary of FGD Gypsum Sample Descriptions

Sample	Plant	Collection Point	Washed	Dewatering	Source Coal	SO_3 Control[1]	Other Control[1]	Absorber Additives[1]
213	06191	Belt, unweathered	Unwashed	Mechanical	Subbituminous	None	LNB	None
216	50207	Pile, unweathered	Washed	Gravity	Subbituminous	None	SCR	None
223	10165	Belt, unweathered	Washed	Mechanical	Bituminous	None	LNB, OFA, SCR	None
224	10164	Belt, unweathered	Washed	Mechanical	Bituminous	Lime + NH_3	SCR, LNCFS II	None
225	10172	Pile, weathered	Unwashed	Gravity	Bituminous	None	LNB, ACI	None
226	01159	Pile, weathered	Unwashed	Gravity	Bituminous	None	LNCFS II, CCOFA/SOFA, SCR	None
227	42197	Belt, unweathered	Washed	Mechanical	Bituminous	DI-Hydrated lime	LNB, SCR	None
228	17202	Impoundment, weathered	Unwashed	Gravity	Bituminous	DI-Hydrated lime	LNB, SCR	None
229	42197	Pile, weathered	Washed	Gravity	Bituminous	DI-Hydrated lime	LNB, SCR	None
230	35406	Pile, unweathered	Washed	Gravity	Bituminous	DI-Trona	LNB, SCR	None
231	33446	Belt, unweathered	Washed	Mechanical	Bituminous	DI-Ammonia	LNB, SCR	None
232	33102	Pile, unweathered	Washed	Gravity	Bituminous	DI-unknown	LNB, SCR	None
233	33107	Pile, weathered	Washed	Gravity	Bituminous	DI-unknown	LNB, SNCR	DBA
234	14088	Belt, unweathered	Washed	Mechanical	Bituminous	None	LNB	None
235	14090	Belt, unweathered	Unwashed	Mechanical	Bituminous	DI-Sodium carbonate	LNB, SCR	DBA or sodium formate
237	14061	Belt, unweathered	Washed	Mechanical	Bituminous	None	LNB, SCR	Sodium formate
238	17154	Belt, unweathered	Washed	Mechanical	Bituminous	None	LNB, SCR	DBA
239	17155	Pile, unweathered	Washed	Gravity	Bituminous	DI-Hydrated lime	LNB, SCR	None
240	17149	Pile, unweathered	Washed	Gravity	Bituminous	DI-Trona	LNB, SCR	None
244	35085	Pile, unweathered	Washed	Gravity	Bituminous	DI-Lime	LNB, SCR	None

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Table 3-1 (continued)
Summary of FGD Gypsum Sample Descriptions

Sample	Plant	Collection Point	Washed	Dewatering	Source Coal	SO_3 Control	Other Control	Absorber Additives
245	35086	Pile, unweathered	Washed	Gravity	Bituminous	DI/FI-unknown	SCR	None
247	38131	Belt, unweathered	Washed	Mechanical	Bituminous	DI-Sodium sulfite	LNB, SCR	Sodium thiosulfate
248	49022	Belt, unweathered	Washed	Mechanical	Bituminous	DI-Trona	LNB, SCR	None
251	49005	Pile, weathered	Unwashed	Gravity	85% Bit.,15% Subbit.	DI-Trona	LNB, SCR	None
253	14090	Belt, unweathered	Washed	Mechanical	Bituminous	DI-Sodium carbonate	LNB, SCR	None
255	38131	Pile, unweathered	Washed	Gravity	Bituminous	DI-Sodium sulfite	LNB, SCR	Sodium thiosulfate
260	13612	Unknown	Unknown	Unknown	Bituminous	None	SCR	None
269	43372	Belt, unweathered	Unwashed	Mechanical	80% Lignite, 20% Subbit.	None	LNB	DBA
270	03587	Belt, unweathered	Unwashed	Mechanical	Bituminous	None	None	None
296	35015	Unknown	Unknown	Unknown	Bituminous	None	None	None
298	33106	Unknown	Unknown	Unknown	Bituminous	None	None	None
304	49003	Unknown	Unknown	Unknown	Bituminous	None	None	None

1. Indicates that some units upstream from the FGD system had this control; DI=duct injection; FI=furnace injection; LNB=low NOx burner; SCR=selective catalytic reduction; SNCR=selective non-catalytic reduction; OFA=overfire air; CCOFA=close-coupled overfire air; SOFA=separated overfire air; LNCFS II=low NOx concentric firing system with separated overfire air; SBS=sodium based solutions; DBA=dibasic acids.

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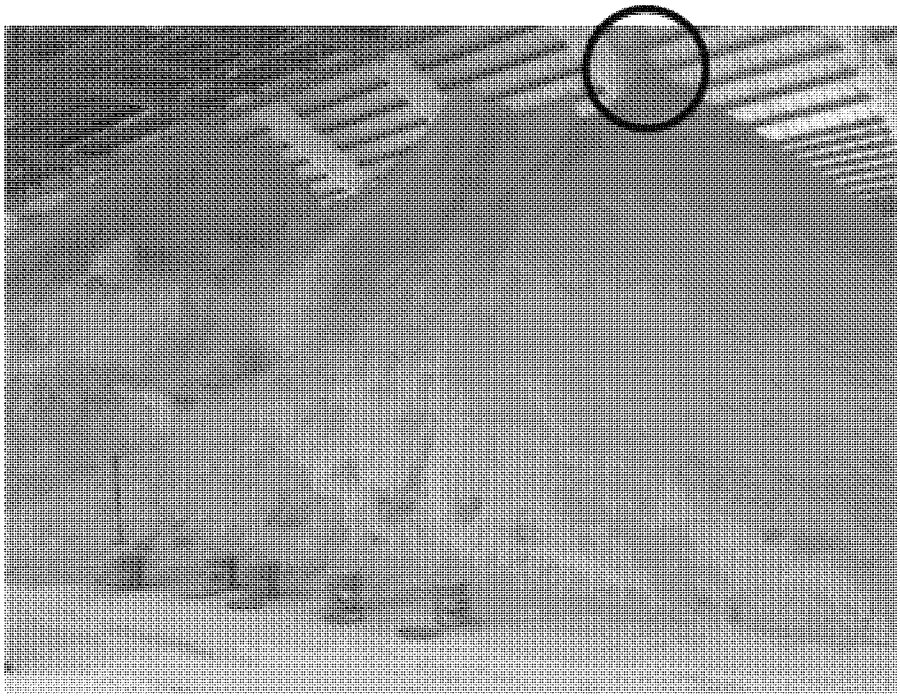

Figure 3-2
Example of an off-belt gypsum sample (224) collected from a fresh indoor pile below the conveyor. Note the falling gypsum inside the circle.

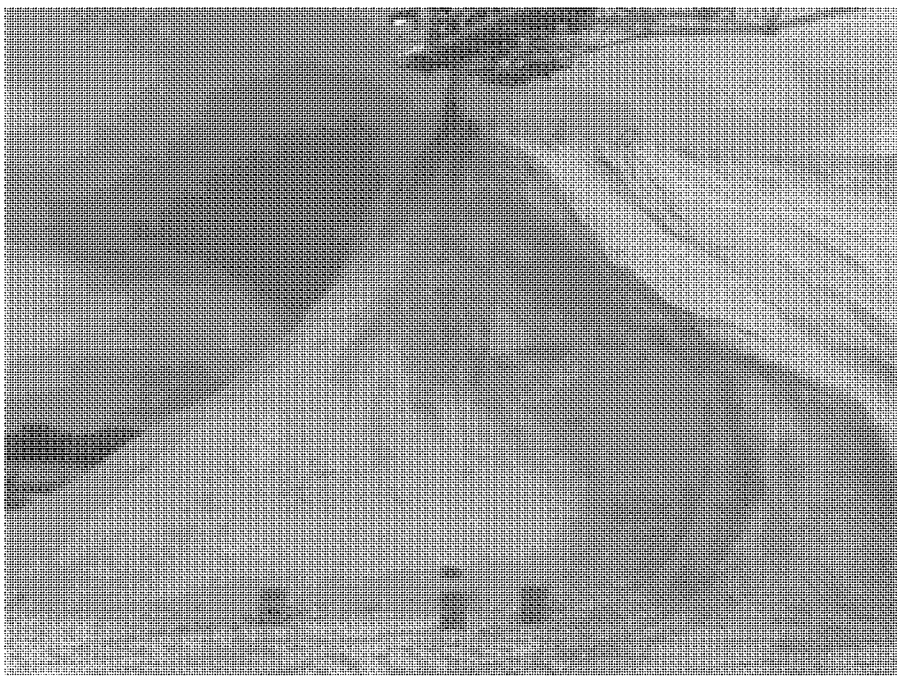

Figure 3-3
Example of an off-belt gypsum sample (238) collected from a fresh outdoor pile below the conveyor. Note the gypsum falling from the conveyor.

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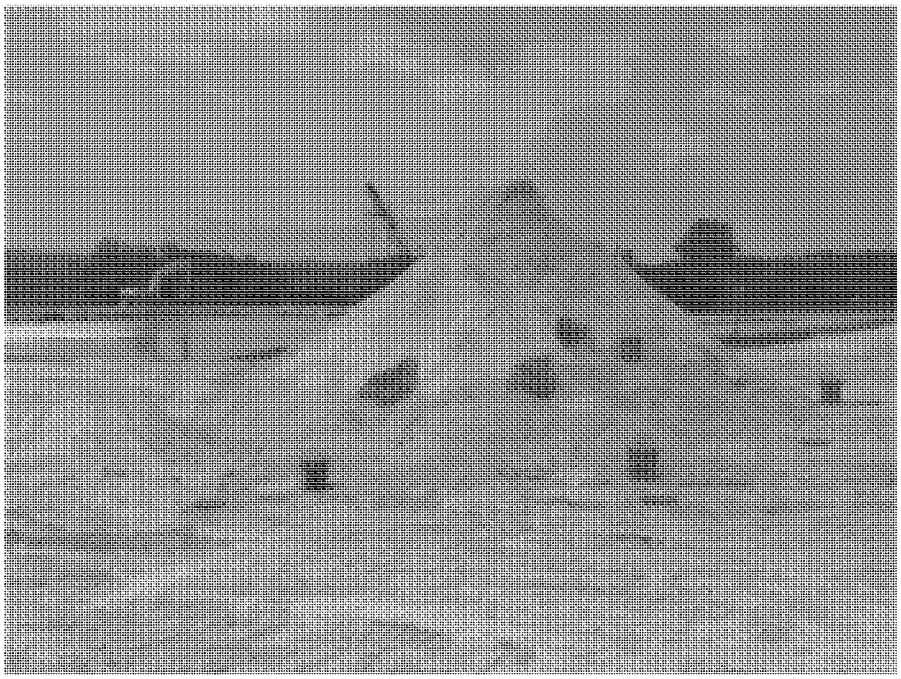

Figure 3-4
Example of an off-pile gypsum sample (225) collected from several locations at an outdoor pile

Mined Gypsum Sample Collection

Mined gypsum samples from 11 different mines were provided by United States Gypsum. The mines were located in the U.S., Mexico, and Canada (Figure 3-1). Samples were collected both before and after crushing, but only the crushed samples (known as land plaster) were tested.

Laboratory Analysis

Three laboratories performed sample analysis. The Ohio State University (OSU) laboratory (Columbus, Ohio) analyzed samples for total composition, Synthetic Precipitation Leaching Procedure (SPLP), Toxicity Characteristic Leaching Procedure (TCLP), and gypsum purity. Arcadis U.S. (Research Triangle Park, NC) analyzed solid and liquid samples for mercury and performed deionized water (DI) leach testing for major anions. The University of Nevada, Reno (UNR) analyzed solid samples for mercury.

Table 3-2 summarizes the elements tested and the methods used.

Total Recoverable Composition

Total composition analysis for all elements except mercury was performed by OSU according to method SW-846 3051a, a microwave assisted aqua regia digestion method. Samples were first oven dried at 100ºC for 24 hours and sieved to < 2 mm. Digests were analyzed using a combination of inductively coupled plasma–atomic emission spectrometry (ICP-AES) and ICP-mass spectrometry (ICP-MS). This method is intended to provide a rapid multi-element acid extraction. A few refractory matrix compounds such as quartz, some silicates, and titanium

dioxide may not be fully dissolved using this analysis, along with other constituents encapsulated in these compounds. These bound elements are typically considered non-mobile in the environment. Ion chromatography was used to analyze for Br and Cl.

Duplicate analyses were performed to provide a measure of precision for samples. A certified reference material (CRM) and digestion blank were included in each set of microwave digestions. CRM recoveries must fall within ± 20% of the certified value or within 95% of the prediction interval of the certified value. Digestion blanks must be below the method detection limit. If any analyte is above the method detection limit, the lowest reported value for that element will be 10 times the digestion blank concentration. Pre-digestion spikes were used to evaluate potential sample matrix problems with digestions or analysis. Spike recoveries must fall within 75 to 125%. ICP calibration standards were prepared using ICP grade standards (SPEX CertiPrep Group, Metuchen, NJ, Assurance ICP Standards). Calibration standards are prepared daily by serial dilution from at least two independent stock standards. Dilutions are done into a matrix comparable to samples. The ICP is calibrated daily and linear calibration must meet the criteria of $R^2 = 0.995$, and calculated standard concentrations must be within 10% for each standard used in the calibration. Initial calibration verification (ICV) is achieved using a certified mix QC standard (SPEX CertiPrep Group LPC standard 1, Fisher Scientific Cat. No. LPC-1-100N). Continuing calibration verification standards are run after every 10 samples. Standards must fall within ± 10% of the certified value.

Total Mercury Analysis

Samples sent for total mercury analysis were lyophilized (freeze dried) within a week of arrival at UNR and then stored at -22°C until analysis. To test the effect of sample storage over time, FGD samples being used at UNR for another experiment were collected, freeze dried and similarly stored and analyzed after 3 months and 5 months. There were no statistically significant differences in concentrations measured in the UNR as-received samples and those analyzed after storage.

Samples were analyzed for total mercury using a Milestone DMA 80 analyzer and EPA Method 7473. There are two developed curves used for determination of total Hg in a sample relative to a calibrated peak area on this instrument, one for samples with high concentrations and one for samples with low concentrations. These two analytical curves were generated using different amounts of NIST 1633 coal fly ash (143 ppb Hg) and NIST 2710 Montana soil (326,000 ppb). Calibration curves were checked using NIST 2709 San Joaquin soil (1,400 ppb) and NIST 2711 Montana soil (6,250 ppm).

During sample analyses, one of every 10 samples was analyzed in triplicate and after every 10 samples the analytical curve was checked using a NIST standard to ensure that the calibration curve remained steady. NIST checks were always within 5% of their reported concentration.

The working range of the Milestone® DMA-80 system is 0.1-600 ng Hg, with a minimum detection limit of 0.01 ng (Milestone operation manual)..

Coefficient of variation for triplicate sample analyses was 4.6 + 1.7% (n = 6) over a concentration range of 6 to 10,000 ng/g.

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Leaching

Three types of leaching tests were performed:

- SW-846 Method 1312 (SPLP) was used to analyze for 27 individual elements. The method was performed as specified using leaching solution 1 (pH = 4.2) with the exception that testing was performed on samples weighing 2 g.
- SW-846 Method 1311 (TCLP) was used to analyze for the eight RCRA metals. The method was performed as specified with the exception that testing was performed on samples weighing 2 g.
- A deionized (DI) water leach test was used to analyze for seven inorganic constituents. The solids were leached in DI water at a 20:1 liquid to solid ratio, filtered, then analyzed.

SPLP and TCLP extracts were analyzed using ICP-AES and ICP-MS as discussed above.

Mercury analysis for SPLP and TCLP extracts was performed by Arcadis U.S. using cold vapor atomic absorption (CVAA) spectrometry according to EPA SW-846 Method 7470A, Mercury in Liquid Waste. Samples were treated with potassium permanganate to reduce possible sulfide interferences. A Perkin Elmer FIMS 100 Flow Injection Mercury System was the instrument used for this analysis. The instrument was calibrated with known standards ranging from 0.25 to 10 µg/L mercury. The detection limit for mercury in aqueous samples is 0.015 µg/L. Matrix spike samples were analyzed for each of the extracts to determine mercury recoveries.

Aqueous concentrations of anions (fluoride, chloride, bromide, nitrate, sulfate, and phosphate) were determined in DI extracts using ion chromatography (IC). Standard USEPA guideline SW-846 Method 9056A was used. These analyses were performed using a Dionex HPLC system and a conductivity detector. Equipment used in the instrument included a AG-12 4-mm guard column, and a AS-12A analytical column. The system uses a carbonate/bicarbonate eluate at 1 mL/min to resolve the peaks.

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Table 3-2
Constituents Analyzed in FGD and Mined Gypsum Samples

Constituent	Total Composition by Method 3051a	Total Composition by Method 7473	SPLP, Method SW-846 1312	TCLP, Method SW-846 1311	Deionized Water Leach Test
Ag				X	
Al	X		X		
As	X		X	X	
B	X		X		
Ba	X		X	X	
Be	X		X		
Br					X
Ca	X		X		
Cd	X		X	X	
Cl					X
Co	X		X		
Cr	X		X	X	
Cu	X		X		
F					X
Fe	X		X		
Hg		X	X	X	
K	X		X		
Li	X				
Mg	X		X		
Mn	X		X		
Mo	X		X		
Na	X		X		
Ni	X		X		
NO_2					X
NO_3					X
P	X		X		
Pb	X		X	X	
PO_4					X
S	X		X		
Sb	X		X		
Se	X		X	X	
Si	X				
SO_4					X
Sr	X		X		
Tl	X		X		
V	X		X		
Zn	X		X		

4
TOTAL COMPOSITION RESULTS

Total composition analytical results are summarized in this section; complete results are listed in Appendix B. Statistical comparisons were made using the procedure described in Appendix C. Probability plots depicting the concentration data are provided in Appendix D.

FGD Gypsum Total Composition Summary

A statistical summary of the FGD gypsum data is presented in Table 4-1 and graphically illustrated in Figure 4-1. As would be expected, the samples were primarily composed of calcium (median 23.7%) and sulfur (median 18.8%). Median concentrations for all other constituents were less than 0.1%. After Ca and S, the twelve constituents with highest median concentration were:[1]

Mg > Fe > Si > Al > K > Sr >> P > Na > B > Mn > Ba > Zn

The median concentrations of Be, Cd, and Tl were less than 0.1 mg/kg, and the median concentrations of Co, Hg, Li, Mo, Pb, and Sb were less than 1 mg/kg.

The concentrations of Ca and S were consistent across the sample set, with a concentration range from maximum to minimum that was less than a factor of 2.0. Most other constituents had a concentration range between one and two orders of magnitude. The greatest variability (slightly greater than two orders of magnitude) was observed with B, Li, Hg, Mg, Mn, and Na.

Washed vs. Unwashed Samples

Twenty of the FGD gypsum samples were washed and five were unwashed. Three other unwashed samples were exposed to rainwater or sluiced, and the status of four samples was not reported—these samples are not included in this comparison. Comparison of the concentration ranges shows that the concentrations of most constituents in unwashed samples generally fall within the upper half of the range of concentrations for the washed samples (Figure 4-2), and most had statistically significant[2] higher concentration ranges (Table 4-2). The most significantly affected constituents were Al, B, Ba, Fe, K, Mn, Na, and Ni.

[1] > indicates that the difference between medians was less than a factor of 5, >> indicates that the difference was greater than a factor of 5.
[2] In the context of this report, "statistically" and "statistically significant" mean that the concentration range of one dataset is statistically different from the other based on the two-group statistical comparison methods described in Appendix C.

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Table 4-1
Statistical Summary of FGD Gypsum Total Composition Data

	Count	% BDL	Min	Median	95th Percentile	Max	Normal	Lognormal
Al	32	0%	61.1	209	1,120	1,610	No	Yes
As	32	0%	1.98	2.86	8.57	11.1	No	No
B	32	0%	2.67	13.2	123	387	No	Yes
Ba	32	0%	0.91	6.38	29.5	55.2	No	Yes
Be	32	28%	BDL	0.020	0.098	0.127	No	No
Ca	32	0%	199,000	237,000	264,000	268,000	Yes	Yes
Cd	32	0%	0.006	0.066	0.234	0.369	No	Yes
Co	32	19%	BDL	0.230	0.578	0.716	No	No
Cr	32	0%	0.45	2.19	8.64	14.8	No	Yes
Cu	32	0%	0.25	1.16	2.61	3.17	Yes	Yes
Fe	32	0%	130	811	1,740	1,820	Yes	No
Hg	31	0%	0.007	0.194	0.917	1.41	No	Yes
K	32	0%	29.0	197	540	744	No	Yes
Li	32	9%	BDL	0.23	1.47	2.01	No	Yes
Mg	32	0%	50.3	1,090	2,960	5,860	No	No
Mn	32	0%	0.83	9.18	62.4	129	No	Yes
Mo	32	0%	0.044	0.560	2.24	4.00	No	Yes
Na	32	0%	10.2	24.0	720	1300	No	No
Ni	32	3%	BDL	1.11	2.41	2.86	Yes	Yes
P	32	0%	4.47	32.3	126	180	No	Yes
Pb	32	16%	BDL	0.98	1.95	8.30	No	No
S	32	0%	156,000	188,000	206,000	208,000	Yes	Yes
Sb	32	0%	0.051	0.151	1.44	4.97	No	No
Se	32	0%	1.44	5.24	26.8	32.0	No	Yes
Si	32	0%	69.0	252	589	1,050	No	Yes
Sr	32	0%	70.5	170	369	405	No	Yes
Tl	31	3%	BDL	0.011	0.035	0.062	No	Yes
V	32	0%	0.32	1.61	5.87	8.57	No	Yes
Zn	32	0%	1.76	5.84	17.0	23.3	No	Yes

Notes:
1) All concentrations in mg/kg.
2) BDL = below method detection limits.
3) Hg was not analyzed in sample 260. There was one Tl outlier that was not included in the analysis (see Appendix C).
4) Normality was determined using the Shapiro-Wilk test (USEPA, 2009).

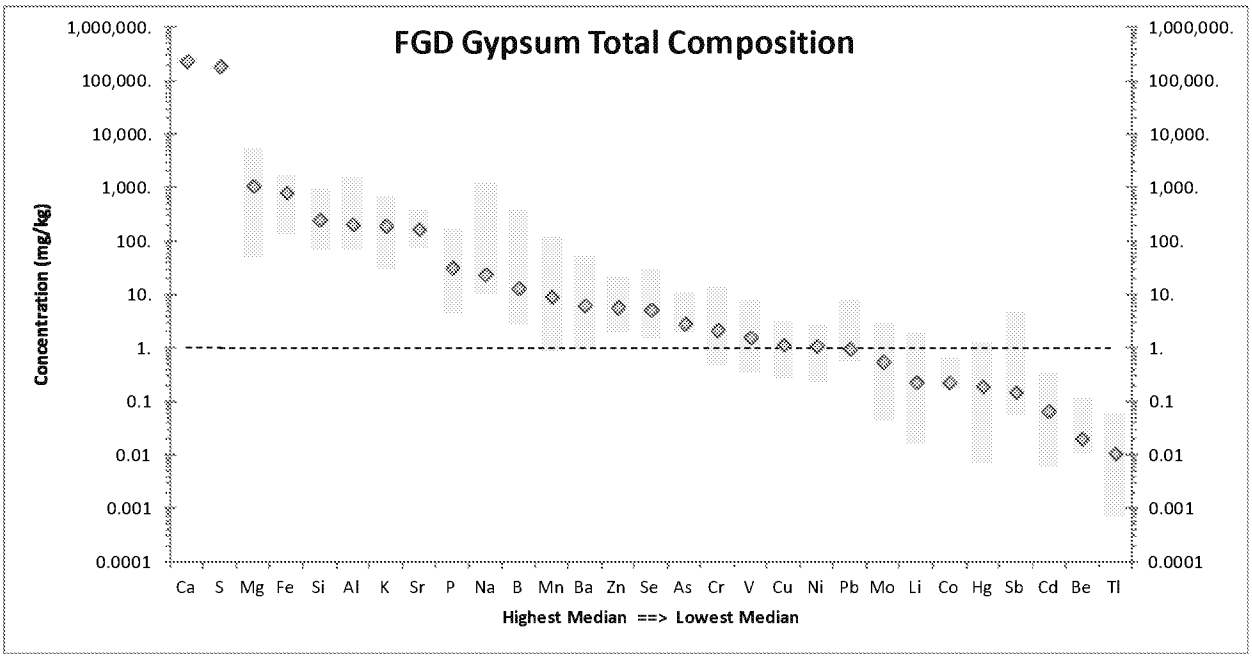

Figure 4-1
Range of total concentrations for FGD gypsum, sorted by median concentration. Median concentrations are shown by diamonds. Dashed line at 1 mg/kg is for reference.

Two of the three unwashed samples not included in the analysis above were sluiced (226 and 228) and one was from an outdoor pile exposed to rainwater (225). Comparison of total composition results from these samples to ranges for washed and unwashed gypsum in Figure 4-2 indicates that the two sluiced samples (226 and 228) fall within the concentration ranges for washed gypsum. Concentrations for some elements of the sample exposed to rainwater (225) were within the range of the washed samples (B, Na), and other elements were within the range of the unwashed samples (Al, Ba, K, Ni). This comparison suggests that sluicing may have a similar effect as washing on total composition of the gypsum samples, but exposure to rainwater may not.

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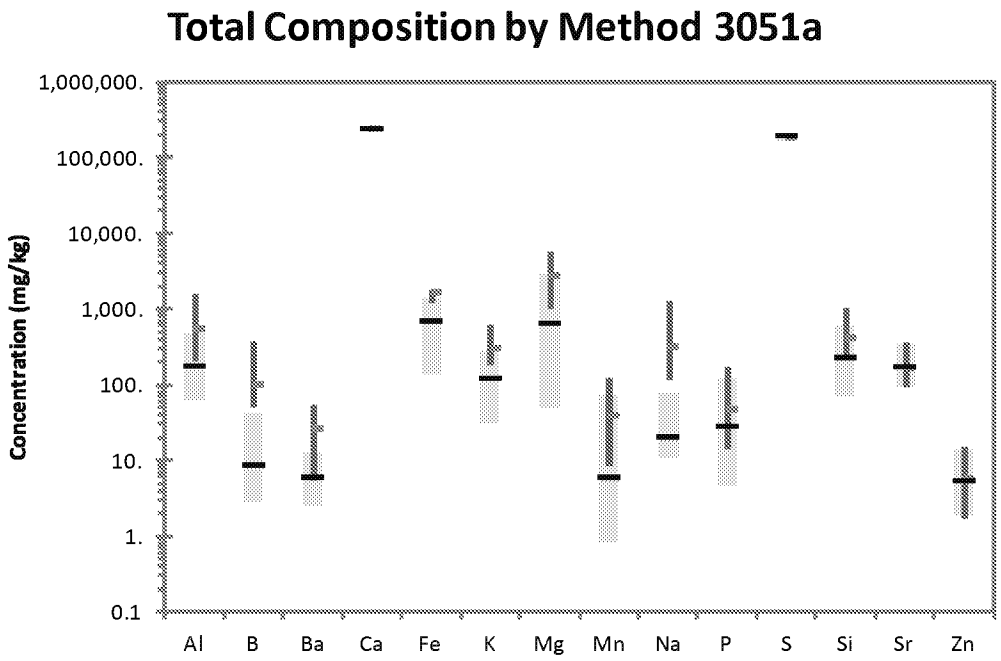

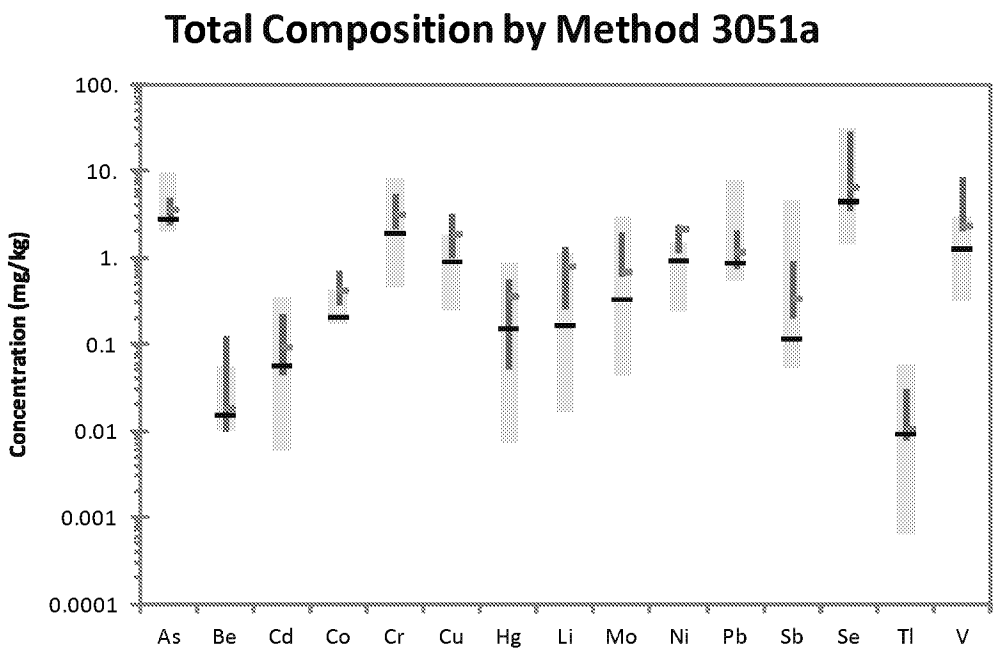

Notes:
- Excludes samples exposed to sluice or rainwater (225, 226, 228) and samples where information on gypsum washing was not available (260, 296, 298, 304).

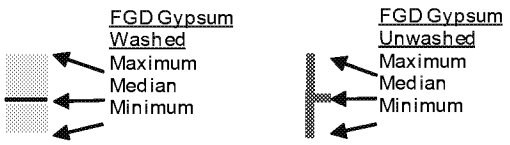

Figure 4-2
Comparison of total composition for washed and unwashed FGD gypsum samples

Table 4-2
Statistical Comparison of Washed and Unwashed FGD Gypsum Samples

	Count		Variance	Washed Gypsum Median (mg/kg)	Unwashed Gypsum Median (mg/kg)
	Washed	Unwashed			
Al	20	5	not equal	*173*	**564**
As	20	5	equal	*2.7*	**3.6**
B	20	5	not equal	*8.6*	**104**
Ba	20	5	not equal	*6.0*	**27**
Be	20	5	not equal	0.015	0.019
Ca	20	5	equal	240,000	246,000
Cd	20	5	equal	*0.057*	**0.094**
Co	20	5	not equal	*0.20*	**0.42**
Cr	20	5	equal	*1.9*	**3.2**
Cu	20	5	equal	*0.88*	**1.9**
Fe	20	5	equal	*687*	**1,700**
Hg	20	5	equal	0.15	0.36
K	20	5	equal	*121*	**309**
Li	20	5	equal	*0.16*	**0.80**
Mg	20	5	equal	*642*	**2,830**
Mn	20	5	equal	*6.0*	**40**
Mo	20	5	equal	*0.32*	**0.69**
Na	20	5	not equal	*20*	**327**
Ni	20	5	equal	*0.90*	**2.2**
P	20	5	equal	*28*	**48**
Pb	20	5	equal	*0.86*	**1.2**
S	20	5	equal	192,000	188,000
Sb	20	5	equal	*0.12*	**0.34**
Se	20	5	equal	4.4	6.6
Si	20	5	equal	*228*	**428**
Sr	20	5	equal	170	172
Tl	20	5	equal	0.009	0.011
V	20	5	not equal	*1.2*	**2.4**
Zn	20	5	equal	5.3	5.9

Explanation for Comparison of Datasets:

- **Bold shade** indicates a median from a dataset with statistically significant higher concentration range than the *italicized* median based on statistical analysis if the variances are equal or graphical analysis if the variances are not equal, as described in Appendix C.
- No formatting indicates that there is no statistical difference between the datasets if the variances are equal, and that the ranges are overlapping or within if the variances are not equal (see Appendix C).

Sorbents Injected for SO_3 Control

This comparison was limited to the 20 washed samples to avoid the confounding effect of washed versus unwashed samples. Within the washed samples, five were from plants injecting lime-based sorbents, six were from plants injecting sodium-based sorbents, and six were from plants that did not inject any sorbent for SO_3 control (three were unknown). Figure 4-3 and Table 4-3 provide a graphical and statistical comparison, respectively, of the lime-based controls to no control, and Figure 4-4 and Table 4-4 the sodium-based controls compared to no control. For both sorbents, concentrations of most constituents were within the range of values for the six samples from plants that did not have SO_3 controls, and there were only minor differences between the groups. Concentrations of Be, Mg, Sr, Tl, and Zn were statistically higher in the lime-based samples compared to no control, while Ca, S, Se, and Si were lower. Only Na had a statistically significant higher concentration in the sodium-based samples compared to no control, while Ca, K, S, Se, and Si concentrations were lower.

Other Observations

FGD Sorbents

Three samples were collected from systems using lime as the sorbent; the rest all used finely ground limestone. Two samples, 247 and 255, used lime sorbent and one sample, 245, used magnesium-enhanced lime (mag-lime). Concentrations for many constituents in these three samples were generally less than the median concentrations, and for sample 245 were among the lowest for all samples (Appendix E, Figure E-1), suggesting that FGD gypsum from systems with lime-based sorbents may have lower total concentrations than gypsum from systems with limestone-based sorbents. This may be due to higher concentrations introduced by the limestone itself, or some other factor unique to those units. Limestone samples were not analyzed as part of this study. It should also be noted that the three lime/mag-lime samples were washed.

SCR and SNCR

Only one washed sample (234) came from a unit that did not have an SCR or SNCR. There were no clear differences noted (Appendix E, Figure E-2). Most constituents analyzed in sample 234 (no SCR or SNCR) fell within the range of values from the other washed FGD gypsum samples, with many near the median values. The exception was Hg, which had lower concentration in sample 234 than in the other samples. Concentrations in the single sample from a system with an SNCR (233) also fell within the range of other washed samples, with the exception of Al, which was higher in the SNCR sample (Appendix E, Figure E-2).

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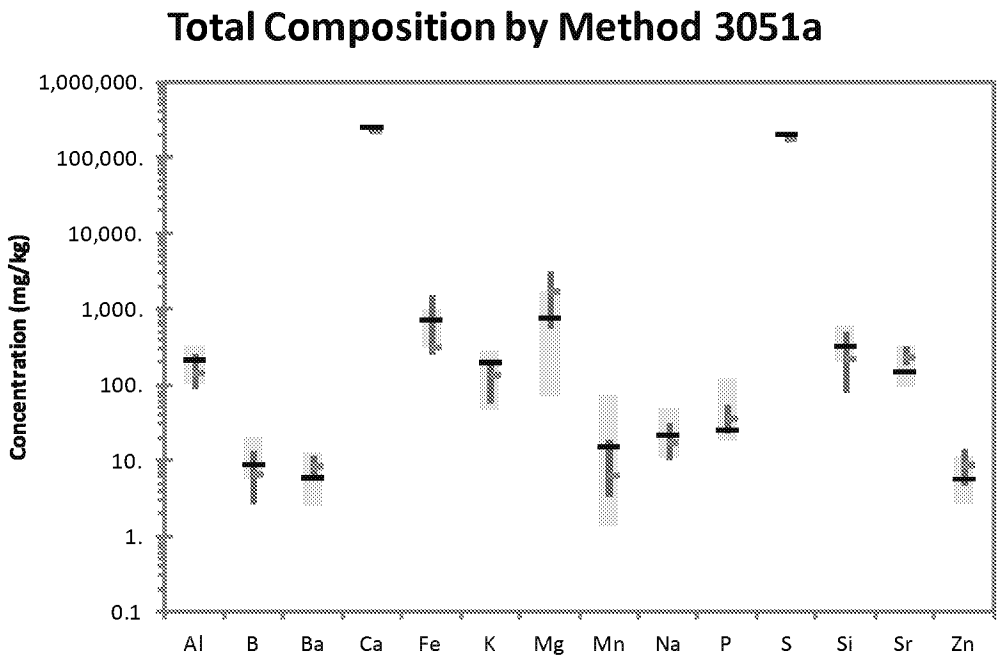
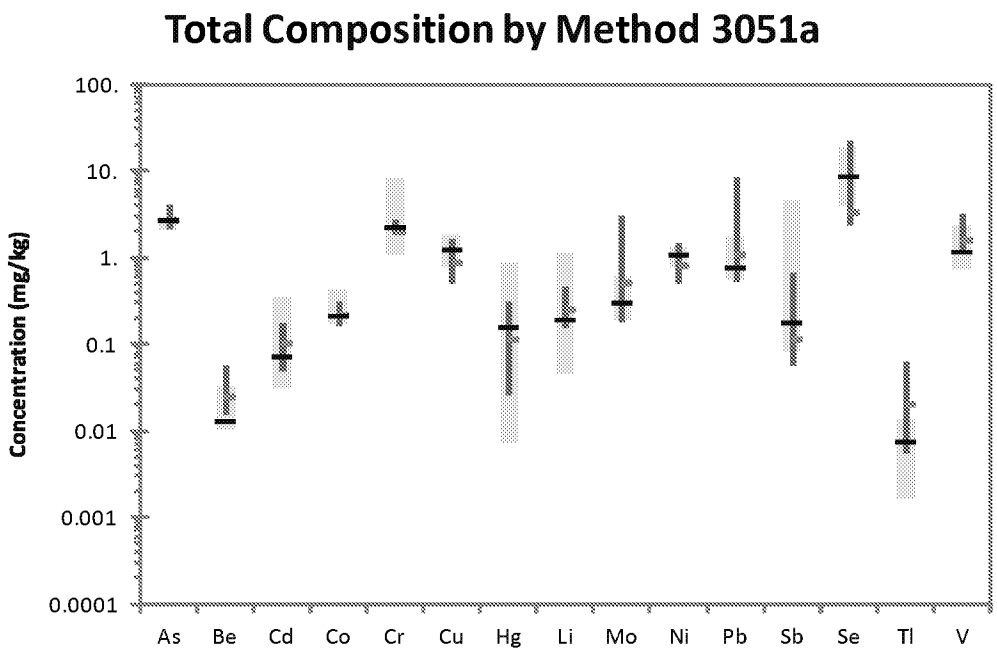




Notes:
- Excludes unwashed samples and samples where information on additives for SO3 control was not available.

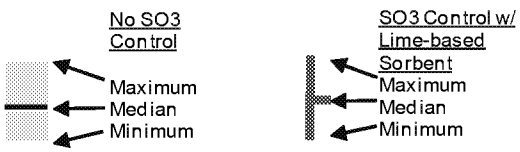


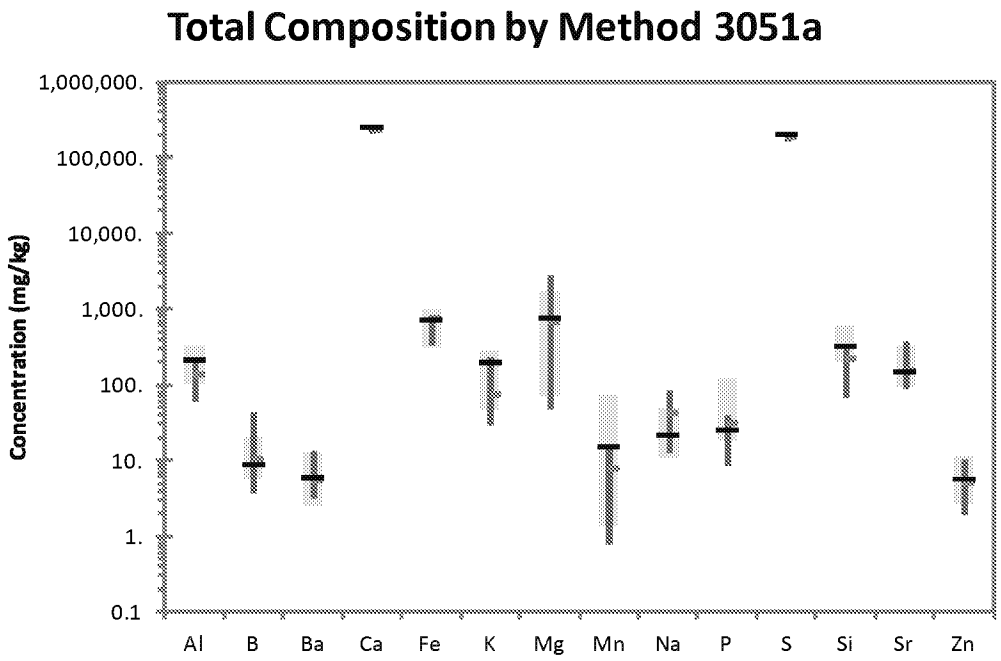
Figure 4-3
Comparison of total composition for samples from plants where lime-based sorbents are used for SO_3 control

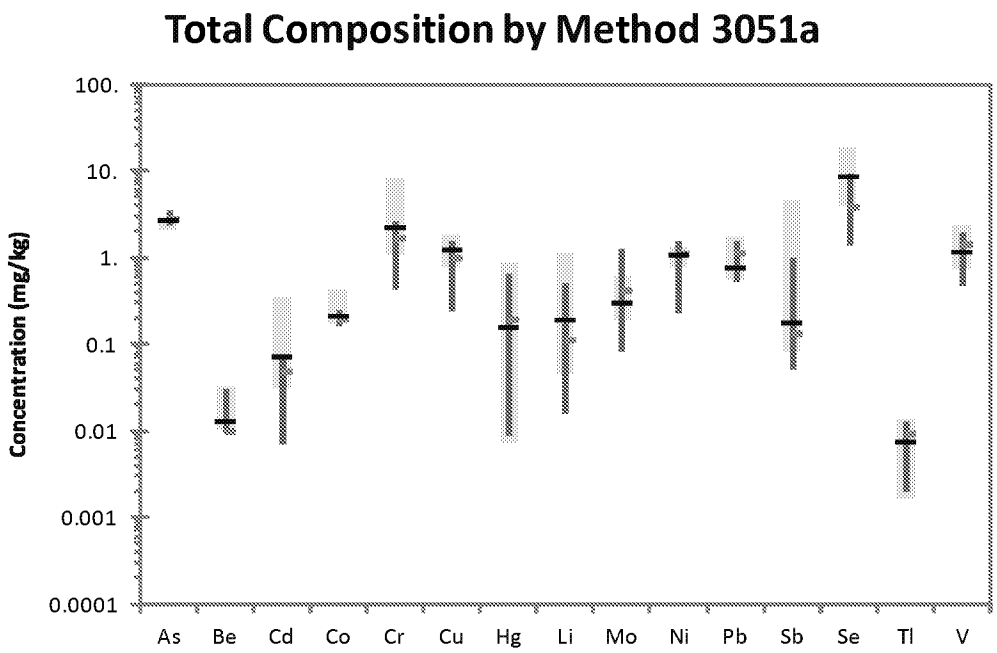
Table 4-3
Statistical Comparison of FGD Gypsum Samples With and Without Lime-Based SO_3 Controls

	Count		Variance	No SO_3 Control Median (mg/kg)	SO_3 Control with Lime-Based Sorbent Median (mg/kg)
	No Control	Lime-Based			
Al	6	5	equal	209	145
As	6	5	equal	2.7	2.7
B	6	5	equal	8.7	6.7
Ba	6	5	equal	5.8	8.5
Be	6	5	equal	*0.013*	**0.025**
Ca	6	5	equal	**249,000**	*230,000*
Cd	6	5	equal	0.07	0.10
Co	6	5	equal	0.21	0.22
Cr	6	5	equal	2.2	2.0
Cu	6	5	equal	1.2	0.89
Fe	6	5	not equal	709	315
Hg	6	5	not equal	0.16	0.12
K	6	5	equal	194	136
Li	6	5	equal	0.19	0.25
Mg	6	5	equal	*753*	**1,730**
Mn	6	5	equal	15	6.5
Mo	6	5	equal	0.30	0.52
Na	6	5	equal	21	18
Ni	6	5	equal	1.1	0.82
P	6	5	equal	25	36
Pb	6	5	equal	0.76	1.1
S	6	5	equal	**200,000**	*183,000*
Sb	6	5	equal	0.18	0.12
Se	6	5	equal	**8.5**	*3.4*
Si	6	5	equal	**323**	*222*
Sr	6	5	equal	*147*	**233**
Tl	5	5	equal	*0.007*	**0.021**
V	6	5	equal	1.1	1.6
Zn	6	5	equal	*5.6*	**8.8**

Explanation for Comparison of Datasets:

- **Bold shade** indicates a median from a dataset with statistically significant higher concentration range than the *italicized* median based on statistical analysis if the variances are equal or graphical analysis if the variances are not equal, as described in Appendix C.
- No formatting indicates that there is no statistical difference between the datasets if the variances are equal, and that the ranges are overlapping or within if the variances are not equal (see Appendix C).





Notes:
- Excludes unwashed samples and samples where information on additives for SO3 control was not available.

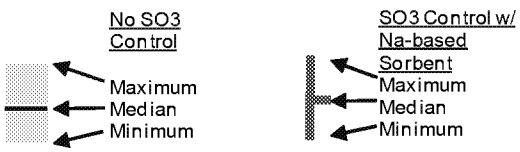


Figure 4-4
Comparison of total composition for samples from plants where sodium-based sorbents are used for SO_3 control

Table 4-4
Statistical Comparison of FGD Gypsum Samples With and Without Sodium-Based SO_3 Controls

	Count		Variance	No SO_3 Control Median (mg/kg)	SO_3 Control with Na-Based Sorbent Median (mg/kg)
	No Control	Sodium-Based			
Al	6	6	equal	209	139
As	6	6	equal	2.7	2.8
B	6	6	equal	8.7	11
Ba	6	6	equal	5.8	5.6
Be	6	6	equal	0.013	<0.010
Ca	6	6	equal	**249,000**	*236,000*
Cd	6	6	equal	0.071	0.049
Co	6	6	equal	0.21	0.20
Cr	6	6	equal	2.2	1.7
Cu	6	6	equal	1.2	1.0
Fe	6	6	equal	709	771
Hg	6	6	equal	0.16	0.20
K	6	6	equal	**194**	*76*
Li	6	6	equal	0.19	0.11
Mg	6	6	equal	753	692
Mn	6	6	equal	15	8.0
Mo	6	6	equal	0.30	0.42
Na	6	6	not equal	*21*	**43**
Ni	6	6	equal	1.1	1.1
P	6	6	equal	25	32
Pb	6	6	equal	0.76	1.2
S	6	6	equal	**200,000**	*191,000*
Sb	6	6	equal	0.18	0.13
Se	6	6	equal	**8.5**	*3.9*
Si	6	6	equal	**323**	*225*
Sr	6	6	equal	147	155
Tl	5	6	equal	0.0074	0.0094
V	6	6	equal	1.1	1.4
Zn	6	6	equal	5.6	5.2

Explanation for Comparison of Datasets:

- **Bold shade** indicates a median from a dataset with statistically significant higher concentration range than the *italicized* median based on statistical analysis if the variances are equal or graphical analysis if the variances are not equal, as described in Appendix C.
- No formatting indicates that there is no statistical difference between the datasets if the variances are equal, and that the ranges are overlapping or within if the variances are not equal (see Appendix C).

Mined Gypsum Total Composition Summary

Mined gypsum total composition data are graphically illustrated in Figure 4-5 and a statistical summary is presented in Table 4-5. Median Ca concentration was 21.3% and median S concentration was 16.7%. After Ca and S, the twelve constituents with highest median concentrations were:

Mg > Al > Sr > Fe > K > Si > Na > Mn > P > Ba > B > Zn

These are the same constituents as listed for FGD gypsum, although the relative ranking differs. Constituents in mined gypsum with median concentrations less than 0.1 mg/kg are the same as for FGD gypsum (Be, Cd, and Tl), along with Hg. Constituents with median concentrations less than 1 mg/kg were Co, Mo, Sb, and Se.

As with FGD gypsum, the concentrations of Ca and S were consistent across the sample set, with a concentration range varying by less than a factor of two. All other constituents, except Tl, had a concentration range between one and two orders of magnitude.

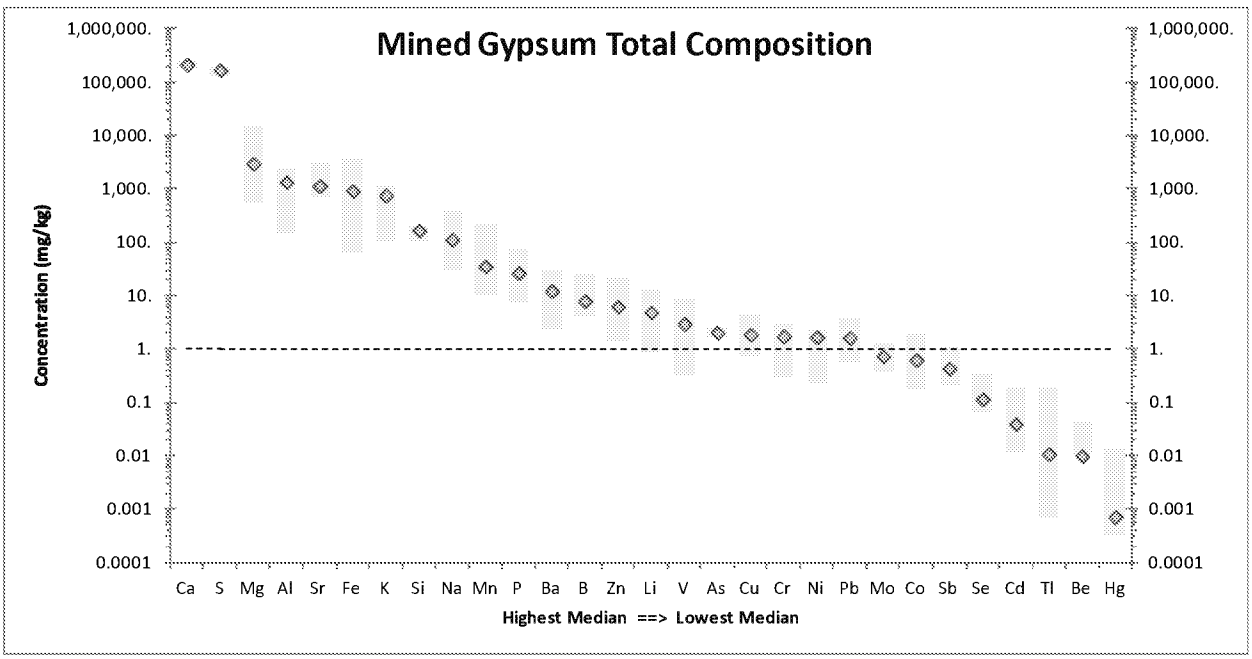


Figure 4-5
Range of total concentrations for mined gypsum, sorted by median concentration. Medians are shown by diamonds. Dashed line at 1 mg/kg is for reference.

Table 4-5
Statistical Summary of Mined Gypsum Total Composition Data

	Count	% BDL	Min	Median	95th Percentile	Max	Normal	Lognormal
Al	11	0%	143	1,330	2,290	2,420	Yes	No
As	11	36%	BDL	2.04	2.50	2.58	Yes	Yes
B	11	0%	4.19	7.96	20.3	25.7	No	Yes
Ba	11	0%	2.22	12.2	28.1	31.0	Yes	Yes
Be	9	56%	BDL	BDL	0.042	0.046	No	No
Ca	11	0%	173,000	213,000	261,000	265,000	Yes	Yes
Cd	11	9%	BDL	0.040	0.161	0.214	No	Yes
Co	11	9%	BDL	0.62	1.62	2.11	No	Yes
Cr	11	0%	0.27	1.75	2.88	3.19	Yes	Yes
Cu	11	0%	0.69	1.87	4.39	4.67	Yes	Yes
Fe	11	0%	58.7	924	2,769	3,770	Yes	Yes
Hg	11	0%	0.00030	0.00072	0.0126	0.0151	No	No
K	11	0%	96	760	1,180	1,230	Yes	No
Li	11	0%	0.79	4.89	12.9	14.2	Yes	Yes
Mg	11	0%	500	2,990	15,400	15,600	No	Yes
Mn	11	0%	10	35	175	241	No	Yes
Mo	11	0%	0.34	0.74	1.24	1.30	Yes	Yes
Na	11	0%	29	113	388	419	Yes	Yes
Ni	11	9%	BDL	1.68	2.22	2.33	Yes	Yes
P	11	0%	7.3	26.5	62.4	74.7	Yes	Yes
Pb	11	18%	BDL	1.64	3.29	4.08	Yes	Yes
S	11	0%	119,000	167,000	210,000	211,000	Yes	Yes
Sb	11	0%	0.20	0.44	1.18	1.19	No	Yes
Se	11	36%	BDL	0.12	0.29	0.35	No	Yes
Si	11	0%	100	167	207	209	Yes	Yes
Sr	11	0%	671	1,140	2,420	3,190	No	Yes
Tl	11	9%	BDL	0.011	0.158	0.200	No	Yes
V	11	0%	0.32	2.97	7.34	9.17	Yes	Yes
Zn	11	0%	1.4	6.2	19.7	23.5	No	Yes

Notes:
1) All concentrations in mg/kg
2) BDL = below method detection limits.
3) There were two Be outliers (see Appendix C).
4) Normality was determined using the Shapiro-Wilk test (USEPA, 2009).

Comparison of FGD Gypsum and Mined Gypsum Total Composition Data

A statistical comparison of total composition results for the FGD and mined gypsum samples is listed in Table 4-6, and side-by-side graphical comparisons are presented in Figures 4-6 and 4-7.

Results of this comparison indicate that 19 of the 29 constituents analyzed have similar or lower concentration ranges in FGD gypsum compared to mined gypsum. Ten constituents had statistically significant higher median concentrations in FGD gypsum: As, B, Be, Ca, Cd, Cr, Hg, S, Se, and Si. Most of these differences were relatively small (less than a factor of 2 difference), with the exception of Se and Hg. Mined gypsum medians were statistically higher than FGD gypsum for 13 constituents, and more than a factor of 2 higher for Al, Co, K, Li, Mg, Mn, Na, Sb, and Sr (Table 4-6).

Gypsum Purity

Purity was measured as the percent of calcium sulfate mineral in the solid sample. By this measure, FGD gypsum demonstrated overall higher purity (90 to 99 percent) than mined gypsum (66 to 98 percent) (Figure 4-8). Purity data are provided at the end of Appendix B.

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Table 4-6
Statistical Comparison of FGD and Mined Gypsum Samples

	Count		Variance	FGD Gypsum Median (mg/kg)	Mined Gypsum Median (mg/kg)
	FGD	Mined			
Al	32	11	not equal	*209*	**1,330**
As	32	11	equal	**2.9**	*2.0*
B	32	11	equal	**13**	*8.0*
Ba	32	11	equal	6.4	12
Be	32	11	equal	**0.020**	*<0.010*
Ca	32	11	equal	**237,000**	*213,000*
Cd	32	11	equal	**0.066**	*0.040*
Co	32	11	not equal	*0.23*	**0.62**
Cr	32	11	equal	**2.2**	*1.7*
Cu	32	11	not equal	*1.2*	**1.9**
Fe	32	11	equal	811	924
Hg	31	11	not equal	**0.19**	*0.0007*
K	32	11	not equal	*197*	**760**
Li	32	11	not equal	*0.23*	**4.9**
Mg	32	11	not equal	*1,090*	**2,990**
Mn	32	11	equal	*9.2*	**35**
Mo	32	11	equal	*0.56*	**0.74**
Na	32	11	equal	*24*	**113**
Ni	32	11	equal	1.1	1.7
P	32	11	equal	32	27
Pb	32	11	equal	*0.98*	**1.6**
S	32	11	equal	**188,000**	*167,000*
Sb	32	11	equal	*0.15*	**0.44**
Se	32	11	not equal	**5.2**	*0.12*
Si	32	11	not equal	**252**	*167*
Sr	32	11	not equal	*170*	**1,140**
Tl	31	11	not equal	0.011	0.011
V	32	11	equal	*1.6*	**3.0**
Zn	32	11	equal	5.8	6.2

Explanation for Comparison of Datasets:

- **Bold shade** indicates a median from a dataset with statistically significant higher concentration range than the *italicized* median based on statistical analysis if the variances are equal or graphical analysis if the variances are not equal, as described in Appendix C.
- No formatting indicates that there is no statistical difference between the datasets if the variances are equal, and that the ranges are overlapping or within if the variances are not equal (see Appendix C).

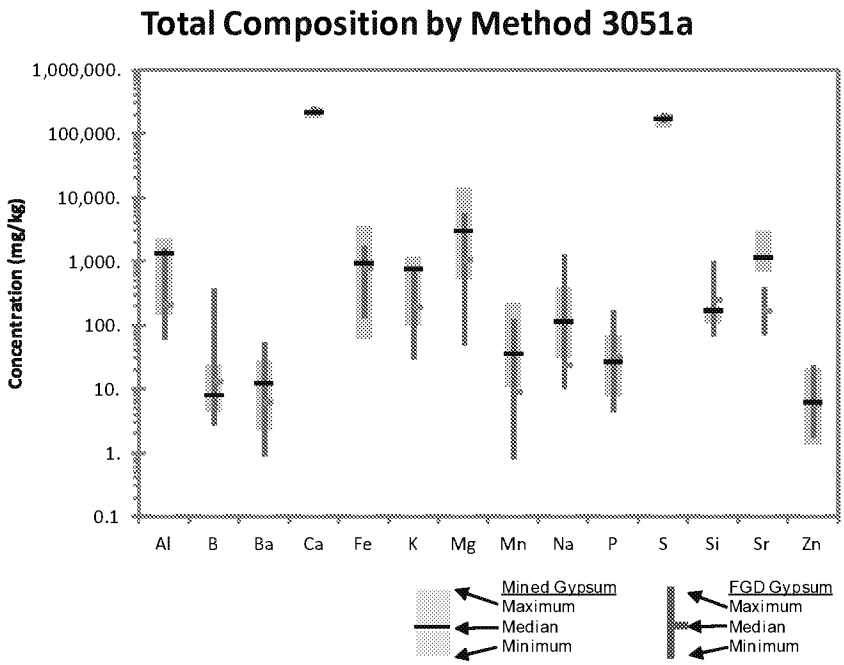

Figure 4-6
Comparison of total concentrations for FGD and mined gypsum, for the constituents with highest median concentration, sorted alphabetically

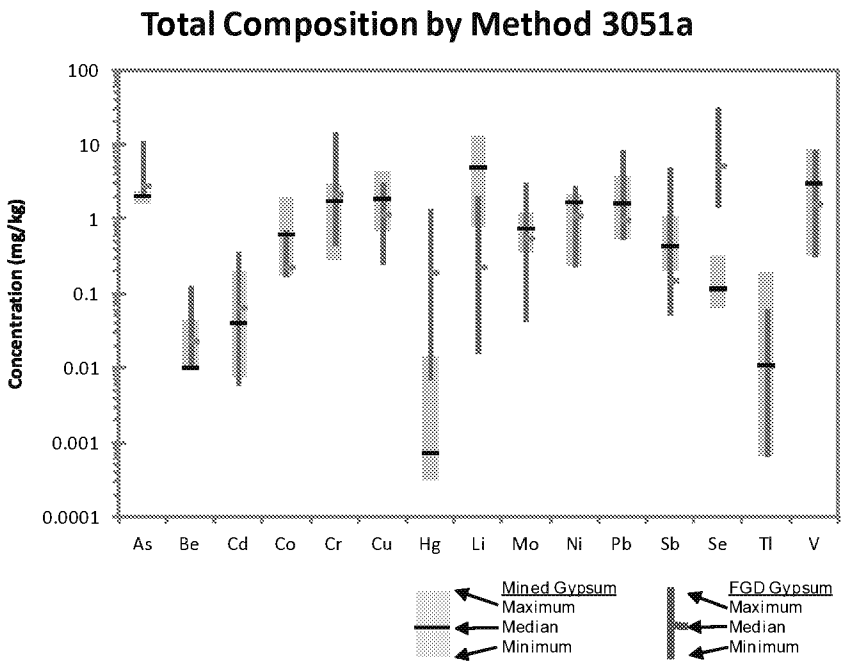

Figure 4-7
Comparison of total concentrations for FGD and mined gypsum, for the constituents with lowest median concentration, sorted alphabetically

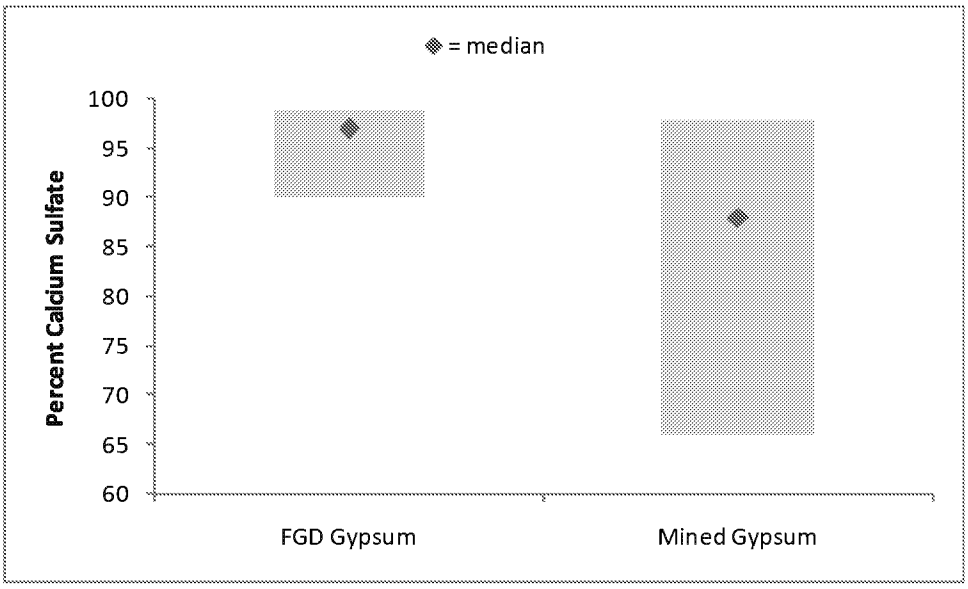

Figure 4-8
Range of calcium sulfate percentages for FGD gypsum and mined gypsum

5
LEACHING RESULTS

Leaching results are summarized in this section; complete results are listed in Appendix B. Statistical comparisons were made using the procedure described in Appendix C. Probability plots depicting the concentration data are provided in Appendix D.

TCLP Extracts

The TCLP test is currently used to determine if a waste material is hazardous under the characteristic criteria in the Resource Conservation and Recovery Act (RCRA; 40 CFR 261.24). The test uses an organic acid leachant to simulate leaching in a municipal solid waste landfill. TC limits have been established for eight metals: Ag, As, Ba, Cd, Cr, Hg, Pb, and Se. A waste is classified as hazardous by characteristic if it exceeds one or more of the TC limits.

TCLP results for the 32 FGD gypsum samples and 11 mined gypsum samples are provided in Tables 5-1 and 5-2, respectively. All results for both gypsum types are well below the TC limit for hazardous waste, typically by two orders of magnitude or more.

Table 5-1
Statistical Summary of FGD Gypsum TCLP Extract Results

	Unit	TC Limit	MDL	Count	%BDL	Min	Median	95th Percentile	Max
Ag	mg/L	5.0	0.017	32	100%	BDL	BDL	BDL	BDL
As	mg/L	5.0	0.005	32	97%	BDL	BDL	BDL	0.023
Ba	mg/L	100	0.0056	32	0%	0.001	0.040	0.078	0.080
Cd	mg/L	1.0	0.0037	32	81%	BDL	BDL	0.0054	0.0082
Cr	mg/L	5.0	0.018	32	100%	BDL	BDL	BDL	BDL
Hg	mg/L	0.2	0.000015	31	13%	BDL	0.000022	0.00010	0.00058
Pb	mg/L	5.0	0.062	32	100%	BDL	BDL	BDL	BDL
Se	mg/L	1.0	0.089	32	78%	BDL	BDL	0.26	0.45
pH[4]	SU			31	0%	4.8	5.1		6.3

Notes:
1) Hg and pH were not analyzed for sample 260.
2) BDL = below method detection limits.
3) MDL = standard method detection limit; in some cases the MDL for an individual analysis was higher due to laboratory procedures such as dilution. There is no MDL for pH.
4) pH at the end of the TCLP extraction.

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Table 5-2
Statistical Summary of Mined Gypsum TCLP Extract Results

	Unit	TC Limit	MDL	Count	%BDL	Min	Median	95th Percentile	Max
Ag	mg/L	5.0	0.017	11	100%	BDL	BDL	BDL	BDL
As	mg/L	5.0	0.005	11	100%	BDL	BDL	BDL	BDL
Ba	mg/L	100	0.0056	11	0%	0.010	0.047	0.107	0.114
Cd	mg/L	1.0	0.0037	11	91%	BDL	BDL	0.0011	0.0059
Cr	mg/L	5.0	0.018	11	100%	BDL	BDL	BDL	BDL
Hg	mg/L	0.2	0.000015	11	36%	BDL	0.000015	0.000017	0.000018
Pb	mg/L	5.0	0.062	11	100%	BDL	BDL	BDL	BDL
Se	mg/L	1.0	0.089	11	100%	BDL	BDL	BDL	BDL
pH[3]	SU			11	0%	4.9	5.4	6.1	6.3

Notes:
1) BDL = below method detection limits.
2) MDL = standard method detection limit; in some cases the MDL for an individual analysis was higher due to laboratory procedures such as dilution. There is no MDL for pH.
3) pH at the end of the TCLP extraction.

SPLP Extracts

The SPLP test is a single point leaching test used to provide a relative leachability of trace constituents exposed to precipitation. The test uses an inorganic acid leachant to simulate leaching by acidic rain. In this study, the SPLP extracts were analyzed for a much larger number of constituents, using lower detection limits, than the TCLP tests, to allow more detailed comparisons. Because the leachant used for SPLP includes both nitric and sulfuric acids, major anions are determined using a deionized water (DI) leachant.

FGD Gypsum SPLP Summary

Tables 5-3 and 5-4 provide a statistical summary of the SPLP and DI leachate data for the 32 FGD gypsum samples; the data are graphically displayed in Figure 5-1.

Final pH values for the SPLP tests ranged from 6.6 to 10.1, with a median of 8.0. Similar values were obtained for the DI water leachate. The highest overall concentrations were observed for SO_4 and Ca. The highest trace metal concentrations were observed for Sr, B, and Al. All As, NO_2, and PO_4 concentrations were below detection limits.

There was little variability (within a factor of two) in the concentration ranges for Be, Ca, and S. B, K, Mn, and Na concentrations exhibited the widest range, varying by more than three orders of magnitude (Figure 5-1).

Table 5-3
Statistical Summary of FGD Gypsum SPLP Extract Concentrations

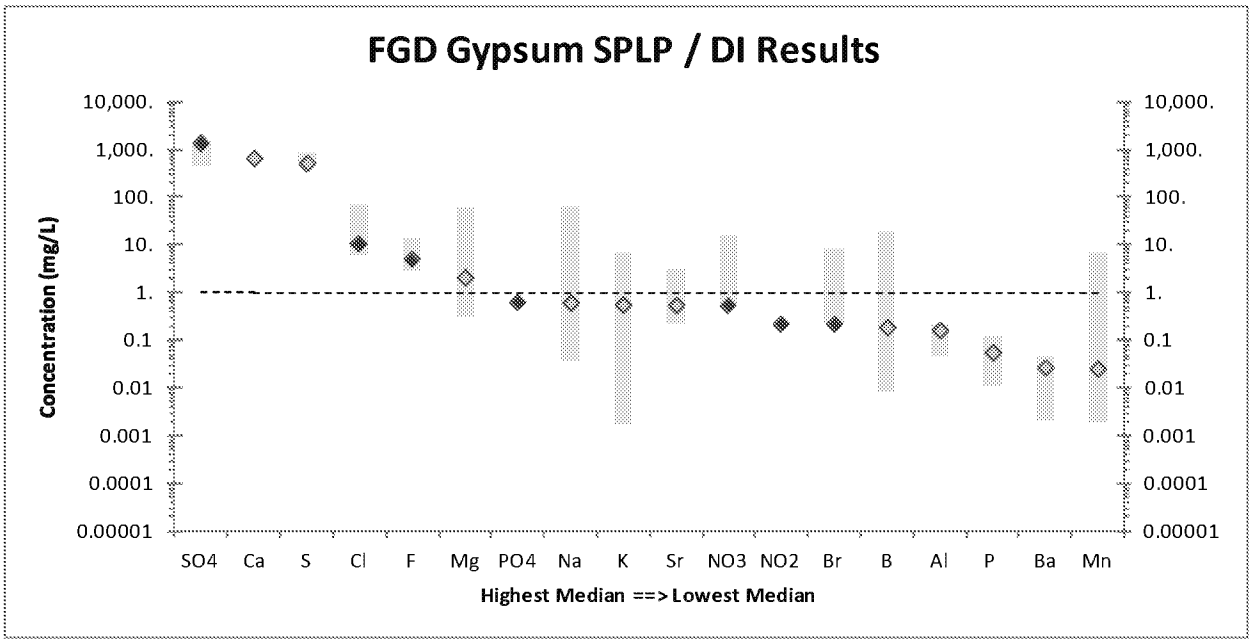
	Unit	MDL	Count	%BDL	Min	Median	95th Percentile	Max
Al	mg/L	0.0047	32	0%	0.043	0.163	0.221	0.240
As	mg/L	0.005	32	100%	BDL	BDL	BDL	BDL
B	mg/L	0.0078	32	34%	BDL	0.189	5.95	20.1
Ba	mg/L	0.00086	32	0%	0.0019	0.027	0.042	0.048
Be	mg/L	0.00061	32	63%	BDL	BDL	0.0007	0.0009
Ca	mg/L	10	32	0%	643	672	766	777
Cd	mg/L	0.00001	32	22%	BDL	0.0001	0.0005	0.0019
Co	mg/L	0.00021	32	0%	0.0023	0.0079	0.0099	0.0106
Cr	mg/L	0.00009	32	19%	BDL	0.00018	0.00041	0.00109
Cu	mg/L	0.00019	32	0%	0.0005	0.0013	0.0023	0.0025
Fe	mg/L	0.00017	32	0%	0.0012	0.0018	0.0142	0.0404
Hg	mg/L	0.000015	31	6%	BDL	0.000063	0.000713	0.001015
K	mg/L	0.0016	32	3%	BDL	0.57	3.66	7.24
Mg	mg/L	0.0012	32	0%	0.29	2.13	54.3	64.3
Mn	mg/L	0.00016	32	0%	0.0018	0.0259	0.713	7.52
Mo	mg/L	0.00004	32	0%	0.00036	0.00249	0.0236	0.0289
Na	mg/L	0.0017	32	0%	0.03	0.62	31.7	70.6
Ni	mg/L	0.0001	32	22%	BDL	0.0002	0.0029	0.0094
P	mg/L	0.0099	32	6%	BDL	0.056	0.123	0.126
Pb	mg/L	0.00001	32	0%	0.00007	0.00010	0.00041	0.00128
S	mg/L	0.035	32	0%	481	521	851	887
Sb	mg/L	0.00001	32	0%	0.00002	0.00021	0.00111	0.00142
Se	mg/L	0.0024	32	0%	0.0024	0.0135	0.187	0.470
Sr	mg/L	0.1	32	0%	0.21	0.55	2.70	3.12
Tl	mg/L	0.000024	32	56%	BDL	BDL	0.00036	0.00074
V	mg/L	0.00008	32	31%	BDL	0.00036	0.00282	0.00662
Zn	mg/L	0.00061	32	3%	BDL	0.0045	0.0171	0.0847
EC	uS/cm		31	0%	4770	6140	6500	8270
pH[4]	SU		31	0%	6.6	8.0	9.6	10.1

Notes:
1) Hg and pH were not analyzed in sample 260.
2) BDL = below method detection limits.
3) MDL = standard method detection limit; in some cases the MDL for an individual analysis was higher due to laboratory procedures such as dilution. There is no MDL for EC and pH.
4) pH at the end of the SPLP extraction.

Table 5-4
Statistical Summary of FGD Gypsum DI Extract Concentrations

	Unit	MDL	Count	%BDL	Min	Median	95th Percentile	Max
F	mg/L	0.11	31	0%	2.7	4.9	12.7	13.7
Cl	mg/L	1.5	31	0%	5.9	10.3	75.7	76.9
NO_2	mg/L	0.22	31	100%	BDL	BDL	BDL	BDL
Br	mg/L	0.22	31	84%	BDL	BDL	8.2	9.0
NO_3	mg/L	0.53	31	65%	BDL	BDL	11.5	16.5
PO_4	mg/L	0.63	31	100%	BDL	BDL	BDL	BDL
SO_4	mg/L	1.2	31	0%	437	1300	1460	1550
EC	uS/cm		31	0%	3530	5100	6500	7380
pH[4]	SU		31	0%	7.7	8.5	9.6	9.7

Notes:
1) DI test not performed for sample 260.
2) BDL = below method detection limits.
3) MDL = standard method detection limit; in some cases the MDL for an individual analysis was higher due to laboratory procedures such as dilution. There is no MDL for EC and pH.
4) pH at the end of the DI extraction.



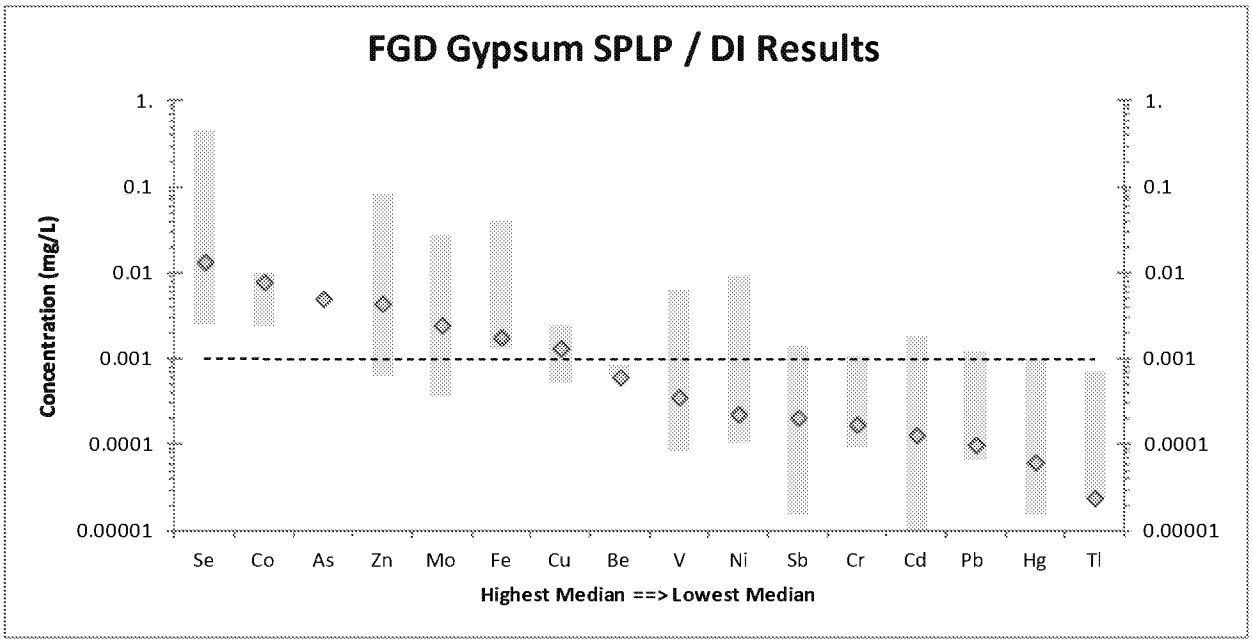


Figure 5-1
Range of concentrations in SPLP and DI extracts from FGD gypsum samples, sorted by median concentration. SPLP medians are indicated by green diamonds, and DI medians are indicated by purple diamonds. Note the different y-axis scales on the two plots. Dashed lines at 1 mg/L on upper plot and 0.001 mg/L on lower plot are for reference.

Comparison of SPLP Concentrations to Total Recoverable Composition

Median and individual concentrations in the SPLP extracts generally increase proportionally with total recoverable composition (Figure 5-2). If the FGD gypsum completely dissolved during the SPLP test, the ratio of total concentration to SPLP concentration (both in ppm) would be 20:1, which is the dilution ratio used in the SPLP test. As shown in Figure 5-2, the ratio is generally much higher than 20:1. Table 5-5 lists the range and median for the percent of the total recoverable composition leached for each constituent during the SPLP tests. Based on median concentrations, B, Na, and Co were the most soluble under the conditions of the SPLP leach test, releasing more than 50% relative to the total recoverable concentration. Conversely, Al, Ba, Ca, Cd, Cr, Cu, Fe, Hg, K, Mg, Mn, Ni, P, Pb, S, Sb, Se, Sr, V, and Zn all released less than 10% of the total recoverable concentration under the SPLP test conditions.

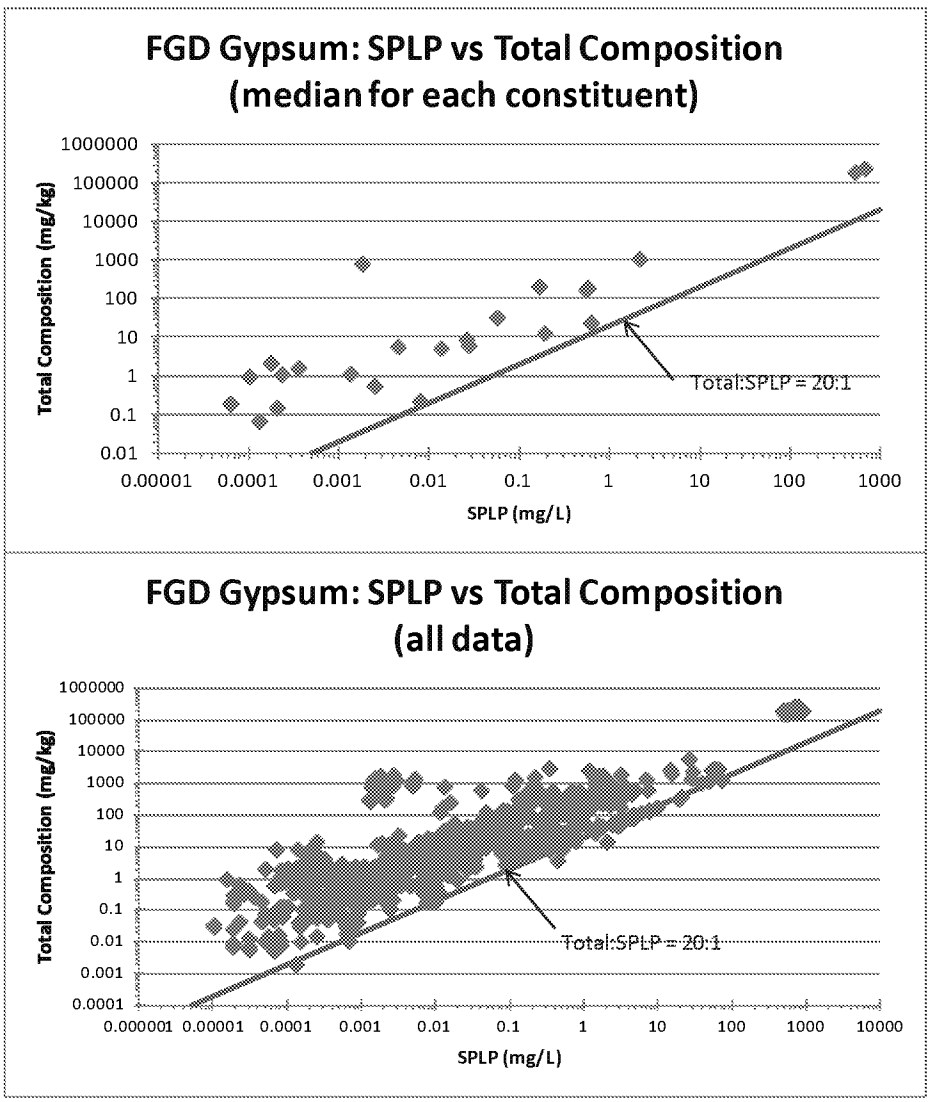


Figure 5-2
Comparison of SPLP extract concentrations to total composition concentrations for all constituents detected in FGD gypsum samples

Table 5-5
Percentage of Each Constituent Dissolved During SPLP Leach Tests on FGD Gypsum Samples

Constituent	Percent Leached[1]		
	Minimum	Median	Maximum
Al	<1%	1%	4%
As	All SPLP results below detection limits		
B	15%	78%	100%
Ba	1%	7%	28%
Be	20%	39%	100%
Ca	5%	6%	7%
Cd	<1%	5%	17%
Co	8%	52%	100%
Cr	<1%	<1%	1%
Cu	<1%	2%	11%
Fe	<1%	<1%	<1%
Hg	<1%	2%	13%
K	2%	9%	34%
Mg	<1%	9%	100%
Mn	<1%	5%	100%
Mo	2%	11%	44%
Na	4%	54%	100%
Ni	<1%	1%	8%
P	<1%	4%	52%
Pb	<1%	<1%	2%
S	5%	6%	10%
Sb	<1%	3%	13%
Se	<1%	6%	34%
Sr	5%	7%	21%
Tl	5%	16%	100%
V	<1%	<1%	6%
Zn	<1%	2%	61%

1. Calculated for samples where solids composition and SPLP tests both yielded detectable results.

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Washed vs. Unwashed Samples

Twenty of the FGD gypsum samples were washed and five were unwashed. Three unwashed samples were exposed to rainwater or sluiced, and the status of four samples was not reported. Comparison of the leachate results shows that the unwashed samples generally had statistically significant higher concentrations of dissolved constituents than the washed samples (Figure 5-3 and Table 5-6). Concentrations of B, Br, Cl, F, K, Mg, Mn, Na, and NO_3 in the unwashed samples were considerably higher (little or no overlap) than the range of concentrations for the washed samples. Bromide was only detected in unwashed FGD gypsum samples. Conversely, concentrations of constituents such as As, Be, Co, Cr, NO_2, P, Pb, PO_4, Sr, and Zn in the washed and unwashed samples were similar (Table 5-6).

The sluiced samples (226 and 228) and sample exposed to rainwater (225) were mixed in terms of whether or not they had concentrations within the range of washed or unwashed samples. Sample 225, which had total composition least resembling the washed samples, had leachate concentrations most closely resembling the washed samples.

Sorbents Injected for SO_3 Control

This comparison was limited to the 20 washed samples to avoid the confounding effect of washed versus unwashed samples. Within the washed samples, five were from plants injecting lime-based sorbents, six were from samples injecting sodium-based sorbents, and six did not inject any sorbent for SO_3 control (three were unknown). Figure 5-4 and Table 5-7 provide a graphical and statistical comparison, respectively, of the lime-based controls to no control, and Figure 5-5 and Table 5-8 the sodium-based controls compared to no control. For both sorbents, concentrations of most constituents were within the range of values for the six samples from plants that did not have SO_3 controls, and there were a few differences between the groups. Concentrations of Tl and V were statistically higher in the lime-based samples compared to no control, while Co, F, Hg, and K were lower. In the Na-based SO_3 controls, B, Co, Fe, Na, P, S, and Zn concentrations were statistically higher compared to no control, while Al, Hg, and Se were lower.

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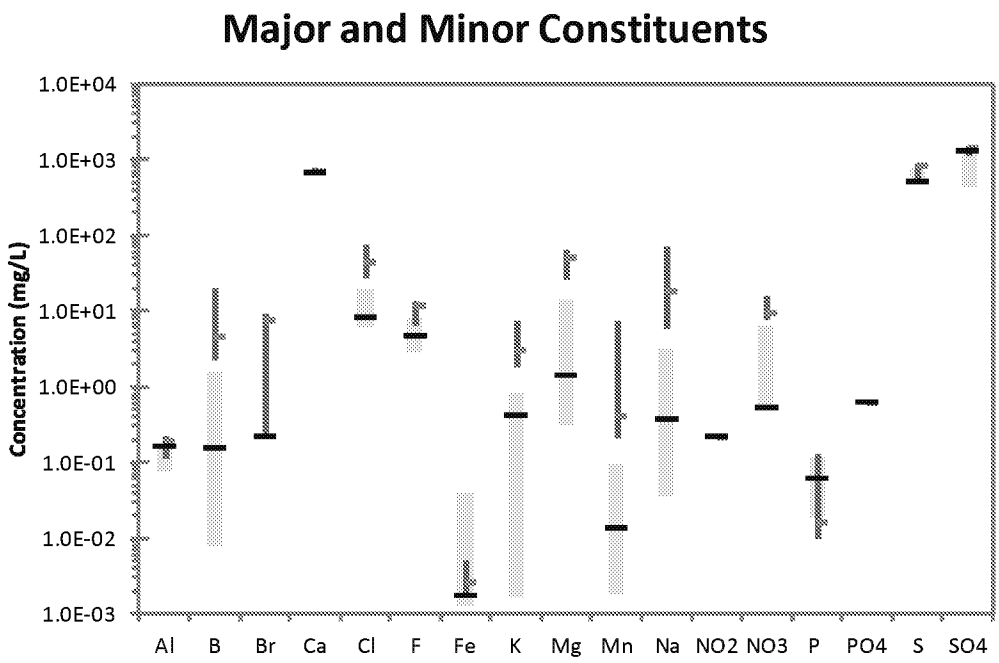

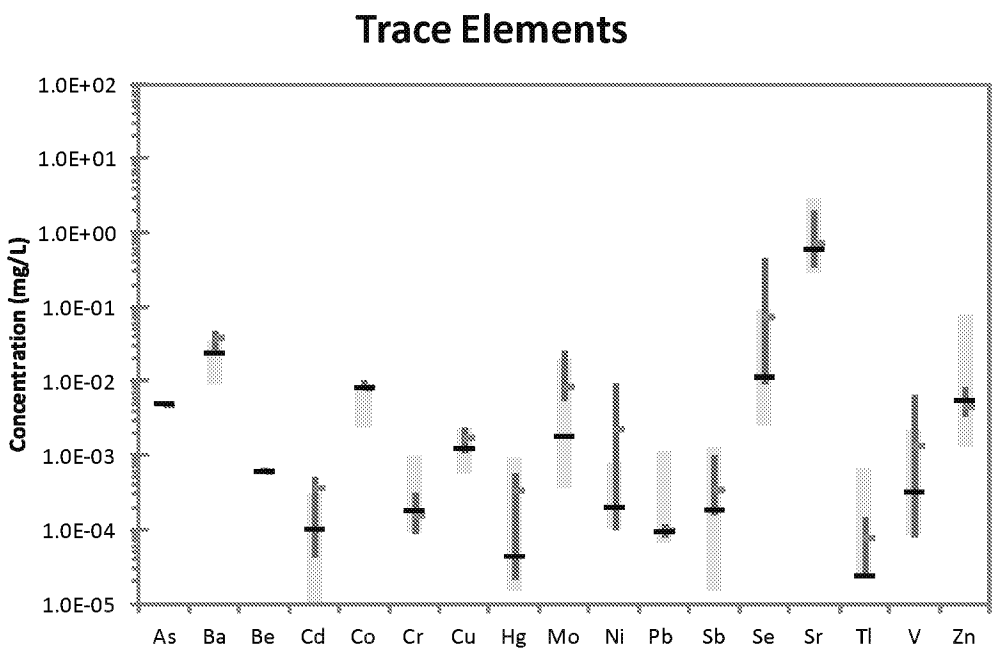

Notes:
- As, NO2, and PO4 all non-detect
- Excludes samples rinced by sluice or rainwater (225, 226, 228) and samples where information on gypsum washing was not available (260, 296, 298, 304).

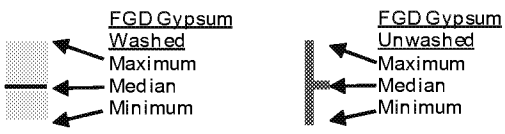

Figure 5-3
Comparison of leachate concentrations for washed and unwashed FGD gypsum

Table 5-6
Statistical Comparison of Washed and Unwashed FGD Gypsum Leachate Samples

	Count		Variance	Washed Gypsum Median (mg/L)	Unwashed Gypsum Median (mg/L)
	Washed	Unwashed			
Al	20	5	equal	*0.16*	**0.20**
As	20	5	BDL	<0.0050	<0.0050
B	20	5	not equal	*0.16*	**4.7**
Ba	20	5	equal	*0.024*	**0.039**
Be	20	5	not equal	<0.00061	0.00063
Br	20	5	equal	*<0.22*	**7.7**
Ca	20	5	equal	*672*	**708**
Cd	20	5	equal	*0.00010*	**0.00038**
Cl	20	5	not equal	*8.2*	**45**
Co	20	5	equal	0.0081	0.0083
Cr	20	5	equal	0.00018	0.00016
Cu	20	5	equal	*0.0012*	**0.0018**
F	20	5	equal	*4.7*	**12**
Fe	20	5	equal	*0.0017*	**0.0027**
Hg	20	5	equal	*0.00004*	**0.00035**
K	20	5	not equal	*0.42*	**3.1**
Mg	20	5	not equal	*1.4*	**52**
Mn	20	5	not equal	*0.014*	**0.42**
Mo	20	5	equal	*0.0018*	**0.0086**
Na	20	5	not equal	*0.37*	**19**
Ni	20	5	not equal	*0.0002*	**0.0023**
NO_2	20	5	BDL	<0.22	<0.22
NO_3	20	5	equal	*<0.53*	**9.6**
P	20	5	equal	0.062	0.016
Pb	20	5	equal	0.00010	0.00010
PO_4	20	5	BDL	<0.63	<0.63
S	20	5	equal	*513*	**845**
Sb	20	5	equal	*0.00019*	**0.00036**
Se	20	5	not equal	*0.011*	**0.075**
SO_4	20	5	equal	*1,290*	**1,440**
Sr	20	5	equal	0.60	0.74
Tl	20	5	equal	*<0.000024*	**0.000080**
V	20	5	not equal	*0.0003*	**0.0014**
Zn	20	5	equal	0.0055	0.0046

Explanation for Comparison of Datasets:

- **Bold shade** indicates a median from a dataset with statistically significant higher concentration range than the *italicized* median based on statistical analysis if the variances are equal or graphical analysis if the variances are not equal, as described in Appendix C.
- No formatting indicates that there is no statistical difference between the datasets if the variances are equal, and that the ranges are overlapping or within if the variances are not equal (see Appendix C).

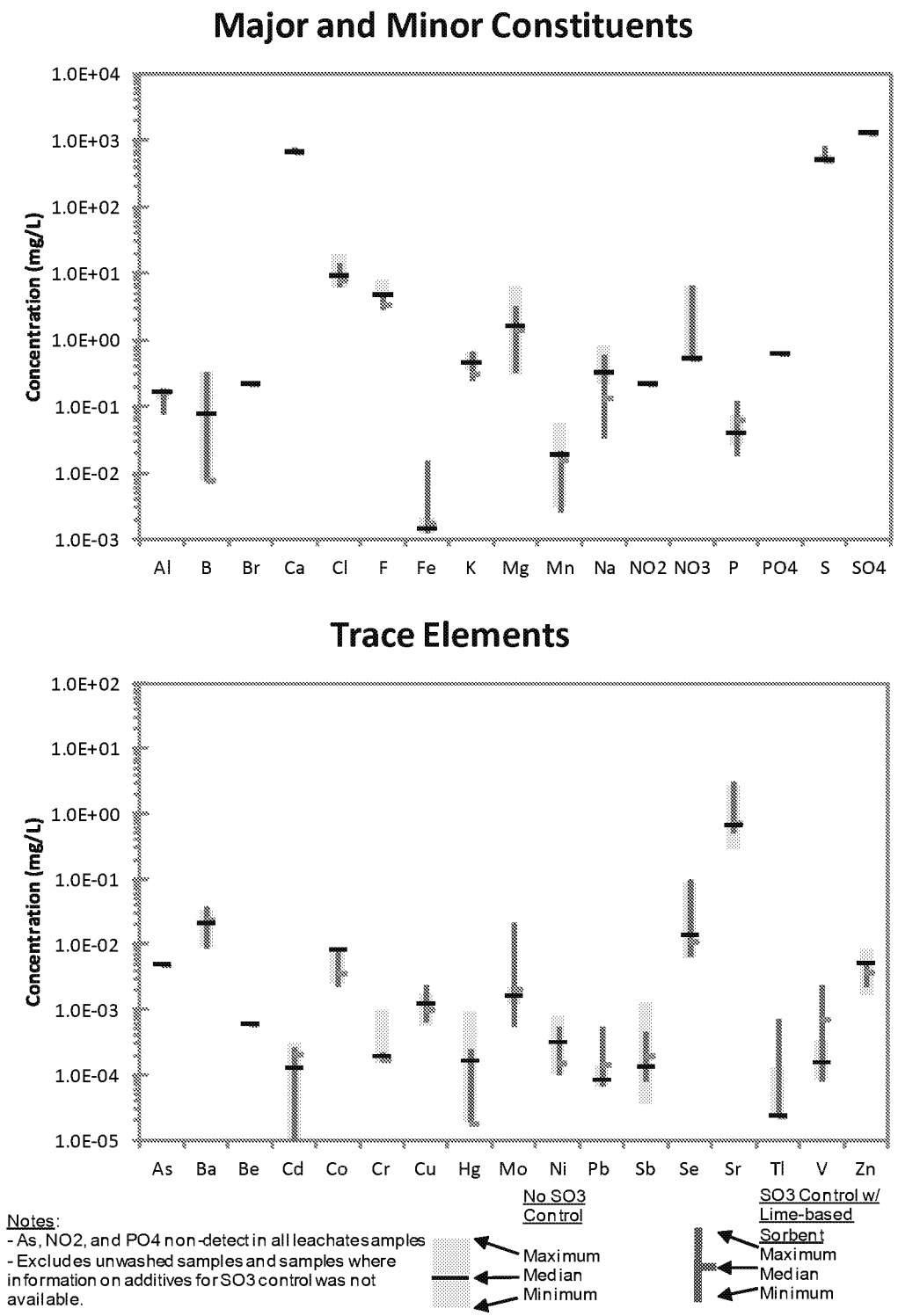

Figure 5-4
Comparison of SPLP concentrations for plants where lime-based sorbents are used for SO_3 control to plants where SO_3 controls were not in use

Table 5-7
Statistical Comparison of FGD Gypsum Leachate Samples With and Without Lime-Based SO_3 Controls

	Count		Variance	No SO_3 Control Median (mg/L)	SO_3 Control with Lime-based Sorbent Median (mg/L)
	No Control	Lime Based			
Al	6	5	equal	0.16	0.17
As	6	5	All BDL	<0.0050	<0.0050
B	6	5	equal	0.071	<0.008
Ba	6	5	equal	0.021	0.024
Be	6	5	equal	<0.00061	<0.00061
Br	6	5	All BDL	<0.22	<0.22
Ca	6	5	equal	672	665
Cd	6	5	equal	0.00013	0.00021
Cl	6	5	equal	9.3	7.9
Co	6	5	equal	**0.0083**	*0.0037*
Cr	6	5	equal	0.00020	0.00018
Cu	6	5	equal	0.0012	0.0010
F	6	5	equal	**4.8**	*3.4*
Fe	6	5	equal	0.0015	0.0018
Hg	6	5	not equal	**0.00017**	*0.00002*
K	6	5	equal	**0.46**	*0.31*
Mg	6	5	equal	1.6	1.4
Mn	6	5	equal	0.019	0.016
Mo	6	5	equal	0.0017	0.0021
Na	6	5	equal	0.32	0.14
Ni	6	5	equal	0.00032	0.00016
NO_2	6	5	All BDL	<0.22	<0.22
NO_3	6	5	equal	<0.53	<0.53
P	6	5	equal	0.040	0.063
Pb	6	5	equal	0.00009	0.00015
PO_4	6	5	All BDL	<0.63	<0.63
S	6	5	equal	513	497
Sb	6	5	equal	0.00014	0.00020
Se	6	5	equal	0.014	0.011
SO_4	6	5	equal	1,290	1,290
Sr	6	5	equal	0.66	0.72
Tl	6	5	not equal	*<0.000024*	**<0.000024**
V	6	5	equal	*0.00008*	**0.00072**
Zn	6	5	equal	0.0052	0.0038

Explanation for Comparison of Datasets:

- **Bold shade** indicates a median from a dataset with statistically significant higher concentration range than the *italicized* median based on statistical analysis if the variances are equal or graphical analysis if the variances are not equal, as described in Appendix C.
- No formatting indicates that there is no statistical difference between the datasets if the variances are equal, and that the ranges are overlapping or within if the variances are not equal (see Appendix C).

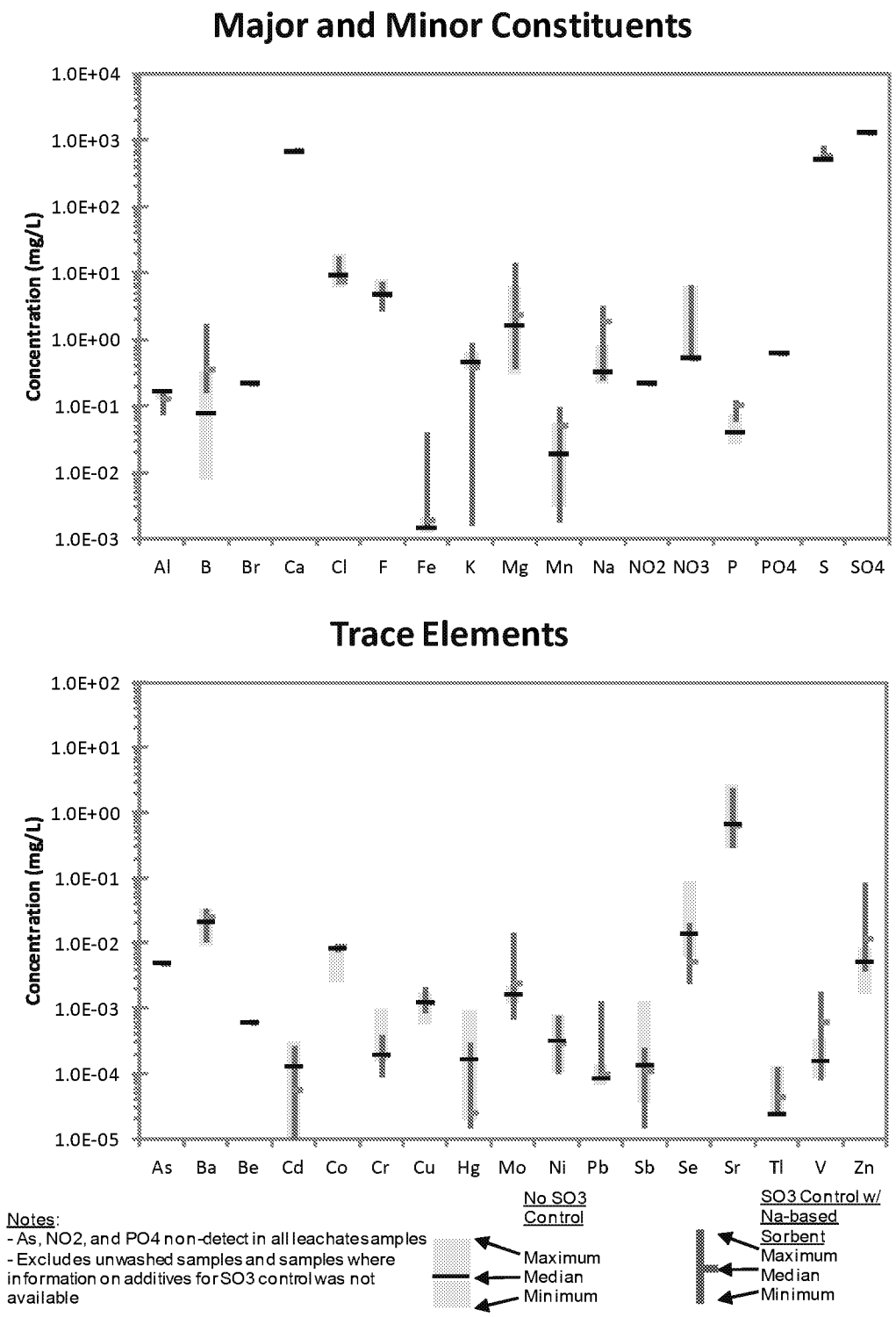

Figure 5-5
Comparison of SPLP concentrations for plants where sodium-based sorbents are used for SO_3 control to plants where SO_3 controls were not in use

Table 5-8
Statistical Comparison of FGD Gypsum Leachate Samples With and Without Sodium-Based SO_3 Controls

	Count		Variance	No SO_3 Control Median (mg/L)	SO_3 Control with Na-based Sorbent Median (mg/L)
	No Control	Na-Based			
Al	6	6	equal	**0.16**	*0.13*
As	6	6	All BDL	<0.0050	<0.0050
B	6	6	equal	*0.071*	**0.36**
Ba	6	6	equal	0.021	0.026
Be	6	6	equal	<0.00061	0.00062
Br	6	6	All BDL	<0.22	<0.22
Ca	6	6	equal	672	700
Cd	6	6	equal	0.00013	0.00006
Cl	6	6	equal	9.3	7.7
Co	6	6	equal	*0.0083*	**0.0091**
Cr	6	6	equal	0.00020	0.00020
Cu	6	6	equal	0.0012	0.0013
F	6	6	equal	4.8	4.8
Fe	6	6	equal	*0.0015*	**0.0020**
Hg	6	6	not equal	**0.00017**	*0.00003*
K	6	6	equal	0.46	0.39
Mg	6	6	equal	1.6	2.4
Mn	6	6	equal	0.019	0.051
Mo	6	6	equal	0.0017	0.0025
Na	6	6	not equal	*0.32*	**1.9**
Ni	6	6	equal	0.00032	0.00030
NO_2	6	6	All BDL	<0.22	<0.22
NO_3	6	6	equal	<0.53	<0.53
P	6	6	equal	*0.04*	**0.10**
Pb	6	6	equal	0.00009	0.00010
PO_4	6	6	All BDL	<0.63	<0.63
S	6	6	equal	*513*	**588**
Sb	6	6	equal	0.00014	0.00011
Se	6	6	equal	**0.014**	*0.005*
SO_4	6	6	equal	1,290	1,300
Sr	6	6	equal	0.66	0.65
Tl	6	6	equal	<0.000024	0.000045
V	6	6	equal	0.00008	0.00063
Zn	6	6	equal	*0.005*	**0.012**

Explanation for Comparison of Datasets:

- **Bold shade** indicate median from a dataset with statistically significant higher concentration range than the *italicized* median based on statistical analysis if the variances are equal or graphical analysis if the variances are not equal, as described in Appendix C.
- No formatting indicates that there is no statistical difference between the datasets if the variances are equal, and that the ranges are overlapping or within if the variances are not equal (see Appendix C).

Other Comparisons

FGD Sorbents

Samples 247, 255, and 245 are from the only systems in the study that used lime for the FGD sorbent; sample 245 used mag-lime. As previously noted, total composition concentrations for these three samples were generally lower than for the samples where limestone sorbent was used, and many constituents in sample 245 were among the lowest in the study (Section 4). However, SPLP leachate concentrations were dispersed throughout the range of other samples (Appendix E, Figure E-3).

SCRs and SNCRs

Only one washed sample (234) came from a unit that did not have an SCR or SNCR. Most constituents analyzed in sample 234 (no SCR or SNCR) and 233 (SNCR) fell within the range of other washed samples. Notable exceptions were SO_4 in the SNCR sample, which had a concentration well below the range of the other samples, and Cr in sample 234, which was well above the range of the other samples (Appendix E, Figure E-4).

Mined Gypsum SPLP Summary

Tables 5-9 and 5-10 provide a statistical summary of the SPLP and DI leachate data for the 32 FGD gypsum samples; the data are graphically displayed in Figure 5-6.

Final pH values for the SPLP tests ranged from 7.1 to 8.6, with a median of 7.4. Similar values were obtained for the DI water leachate. The highest overall concentrations were observed for SO_4 and Ca. The highest trace metal concentrations were observed for Sr, Ba, and Al. All As, B, Br, NO_2, and PO_4 concentrations were below detection limits.

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Table 5-9
Statistical Summary of Mined Gypsum SPLP Extract Concentrations

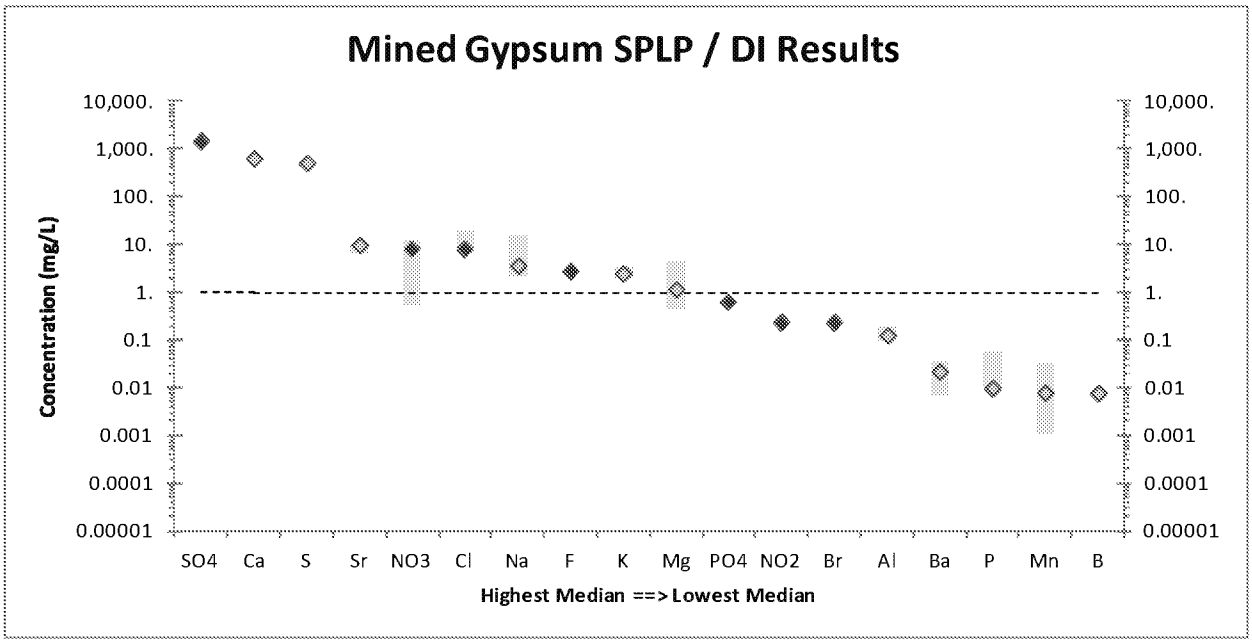
	Unit	MDL	Count	%BDL	Min	Median	95th Percentile	Max
Al	mg/L	0.0047	11	0%	0.089	0.129	0.179	0.202
As	mg/L	0.005	11	100%	BDL	BDL	BDL	BDL
B	mg/L	0.0078	11	100%	BDL	BDL	BDL	BDL
Ba	mg/L	0.00086	11	0%	0.0067	0.0225	0.0338	0.0379
Be	mg/L	0.00061	11	27%	BDL	0.00066	0.000868	0.000905
Ca	mg/L	10	11	0%	641	654	669	674
Cd	mg/L	0.00001	11	82%	BDL	BDL	0.000058	0.00010
Co	mg/L	0.00021	11	0%	0.0027	0.0060	0.0072	0.0074
Cr	mg/L	0.00009	11	45%	BDL	0.00013	0.00043	0.00043
Cu	mg/L	0.00019	11	0%	0.00061	0.00118	0.00385	0.00590
Fe	mg/L	0.00017	11	9%	BDL	0.0019	0.0052	0.0077
Hg	mg/L	0.000015	11	64%	BDL	BDL	0.000022	0.000022
K	mg/L	0.0016	11	0%	1.8	2.5	3.4	3.5
Mg	mg/L	0.0012	11	0%	0.40	1.15	3.73	4.76
Mn	mg/L	0.00016	11	0%	0.0010	0.0081	0.0289	0.0354
Mo	mg/L	0.00004	11	0%	0.00073	0.00341	0.0118	0.0149
Na	mg/L	0.0017	11	0%	2.0	3.7	13.1	16.8
Ni	mg/L	0.0001	11	27%	BDL	0.00031	0.00332	0.00431
P	mg/L	0.0099	11	64%	BDL	BDL	0.059	0.063
Pb	mg/L	0.00001	11	9%	BDL	0.00012	0.00015	0.00015
S	mg/L	0.035	11	0%	507	520	531	534
Sb	mg/L	0.00001	11	9%	BDL	0.00041	0.00108	0.00109
Se	mg/L	0.0024	10	90%	BDL	BDL	0.00028	0.00248
Sr	mg/L	0.1	11	0%	6.1	9.9	10.9	11.1
Tl	mg/L	0.000024	11	55%	BDL	BDL	0.00088	0.0015
V	mg/L	0.00008	11	0%	0.00013	0.00061	0.00175	0.00220
Zn	mg/L	0.00061	11	9%	BDL	0.0039	0.0096	0.0137
EC	uS/cm		11	0%	4880	5990	6220	6260
pH[4]	SU		11	0%	7.1	7.4	8.2	8.6

Notes:
1) One Se outlier was excluded from the analysis (see Appendix C).
2) BDL = below method detection limits.
3) MDL = standard method detection limit; in some cases the MDL for an individual analysis was higher due to laboratory procedures such as dilution. There is no MDL for EC and pH.
4) pH at the end of the SPLP extraction.

Table 5-10
Statistical Summary of Mined Gypsum DI Extract Concentrations

	Unit	MDL	Count	%BDL	Min	Median	95th Percentile	Max
F	mg/L	0.11	11	0%	2.6	2.7	2.8	2.8
Cl	mg/L	1.5	11	0%	6.1	7.7	16.2	21.8
NO_2	mg/L	0.22	11	100%	BDL	BDL	BDL	BDL
Br	mg/L	0.22	11	100%	BDL	BDL	BDL	BDL
NO_3	mg/L	0.53	11	27%	BDL	8.1	12.3	12.6
PO_4	mg/L	0.63	11	100%	BDL	BDL	BDL	BDL
SO_4	mg/L	1.2	11	0%	1340	1390	1440	1460
EC	uS/cm		11	0%	4980	5060	5260	5300
pH[3]	SU		11	0%	7.6	8.3	8.9	9.0

Notes:
1) BDL = below method detection limits.
2) MDL = standard method detection limit; in some cases the MDL for an individual analysis was higher due to laboratory procedures such as dilution. There is no MDL for EC and pH.
3) pH at the end of the DI extraction.



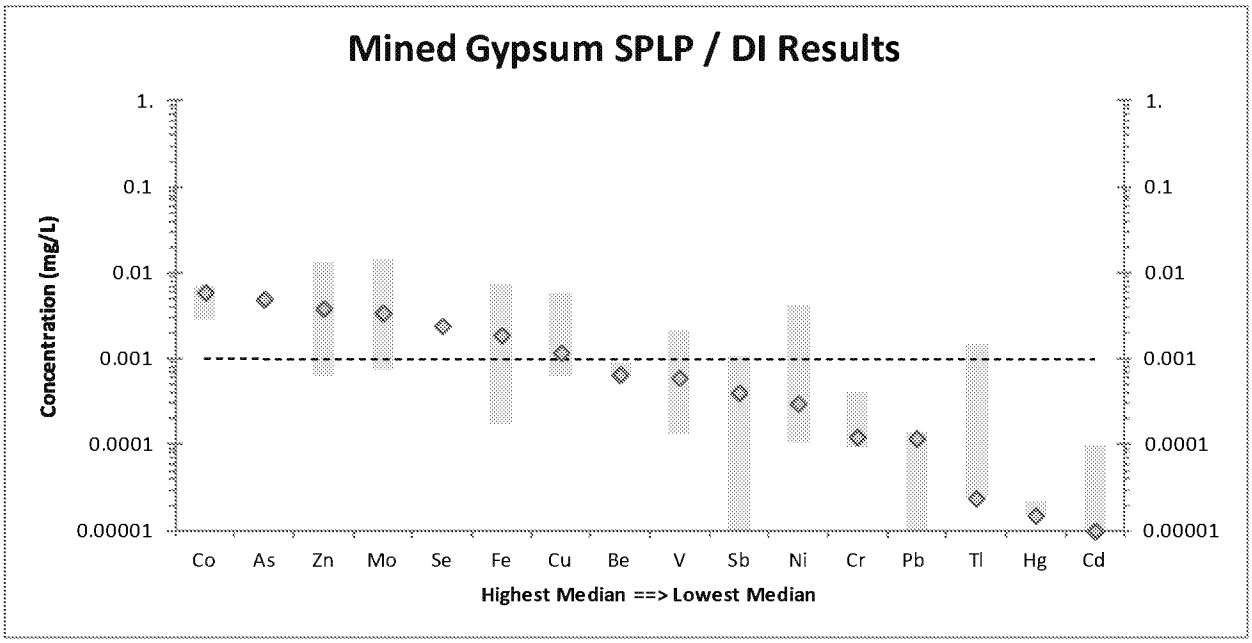


Figure 5-6
Range of concentrations in SPLP and DI extracts from mined gypsum samples, sorted by median concentration. SPLP medians are indicated by green diamonds, and DI medians are indicated by purple diamonds. Note the different y-axis scales on the two plots. Dashed lines at 1 mg/L on upper plot and 0.001 mg/L on lower plot are for reference.

Comparison of FGD Gypsum and Mined Gypsum SPLP Leachate Concentrations

Side-by-side graphical comparisons of leachate concentrations are presented in Figures 5-7, 5-8, and 5-9, and a statistical comparison of total composition results for the FGD and mined gypsum leachate samples is listed in Table 5-11.

Results of this comparison indicate that 22 of the 34 constituents analyzed have similar or lower concentration ranges in SPLP leachate from FGD gypsum compared to mined gypsum. Twelve constituents—B, Ba, Br, Ca, Cd, Co, Cr, F, Hg, Mn, P, and Se—had statistically significant higher concentrations in the FGD sample set. The constituents in the FGD gypsum extracts with the highest concentrations relative to the mined gypsum extracts were B, Hg, and Se, although the median concentrations of all three of these constituents were relatively low (Table 5-11). Boron was not detected in mined gypsum samples, and was detected at concentrations ranging from 0.1 to 20 mg/L in FGD gypsum samples, with the highest concentrations (> 2 mg/L) occurring in unwashed samples. Mercury was detected in only 36 percent of the mined gypsum SPLP leachate samples, compared to 94 percent of the FGD samples. Selenium was detected in only 10 percent of the mined gypsum SPLP leachate samples, compared to 100 percent of the FGD samples. The highest Se concentrations (> 0.1 mg/L) were in unwashed samples.

In the outlier analysis (see Appendix C), three potential outliers were identified in the mined gypsum dataset that were included in the analysis (Fe and Zn in sample 303; Cu in sample 295). These results were temporarily excluded from the mined gypsum dataset and the statistics were recalculated. The statistical results without the potential outlier values were the same as the results with the potential outliers (no statistically significant differences between the datasets for Cu, Fe, and Zn).

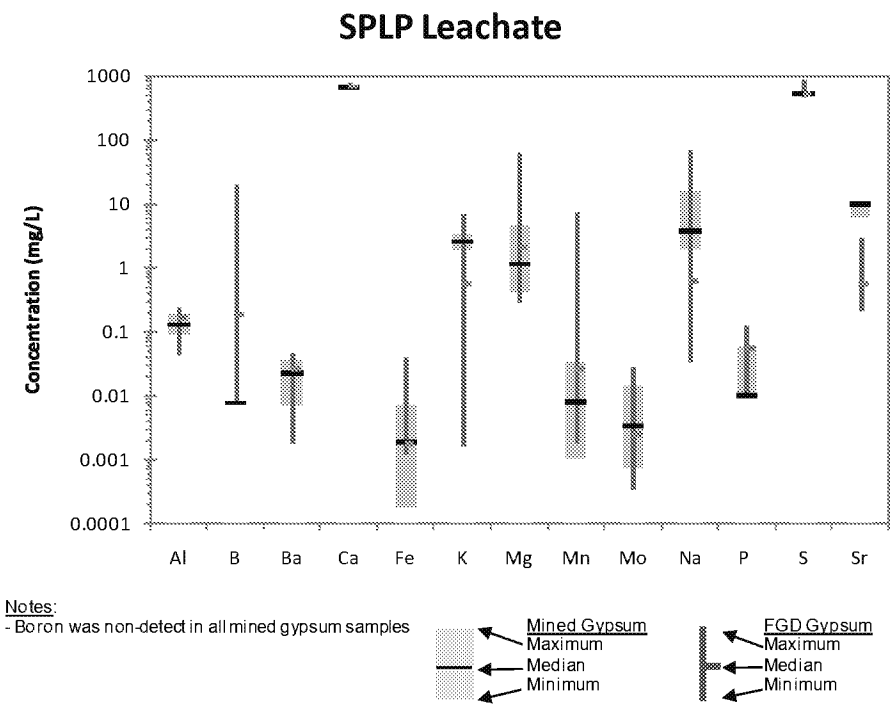


Figure 5-7
Comparison of SPLP extract concentrations for FGD and mined gypsum, for the constituents with highest median concentration, sorted alphabetically

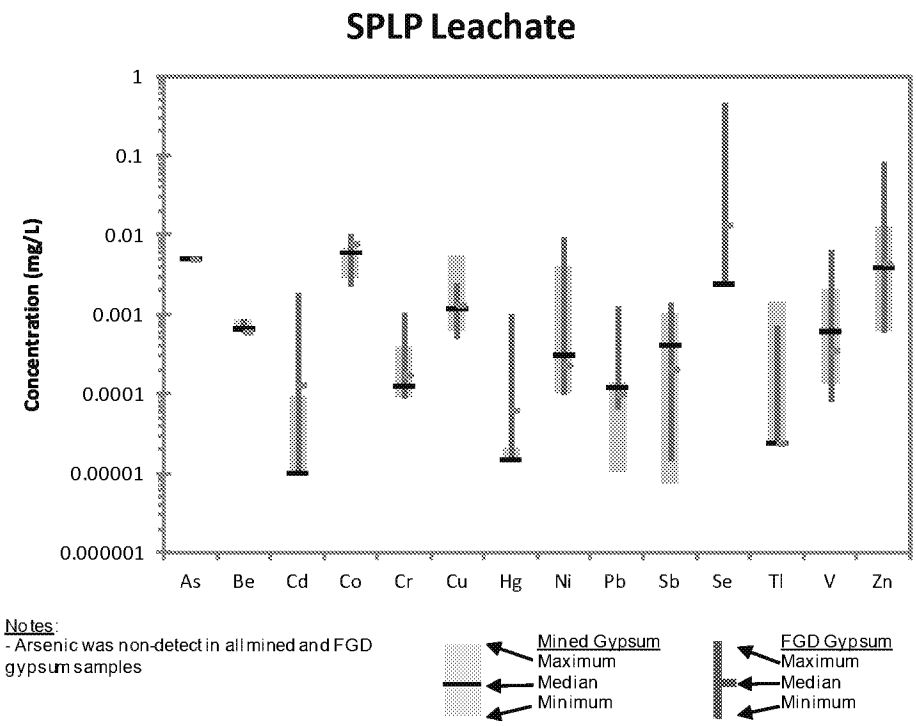


Figure 5-8
Comparison of SPLP extract concentrations for FGD and mined gypsum, for the constituents with lowest median concentration, sorted alphabetically

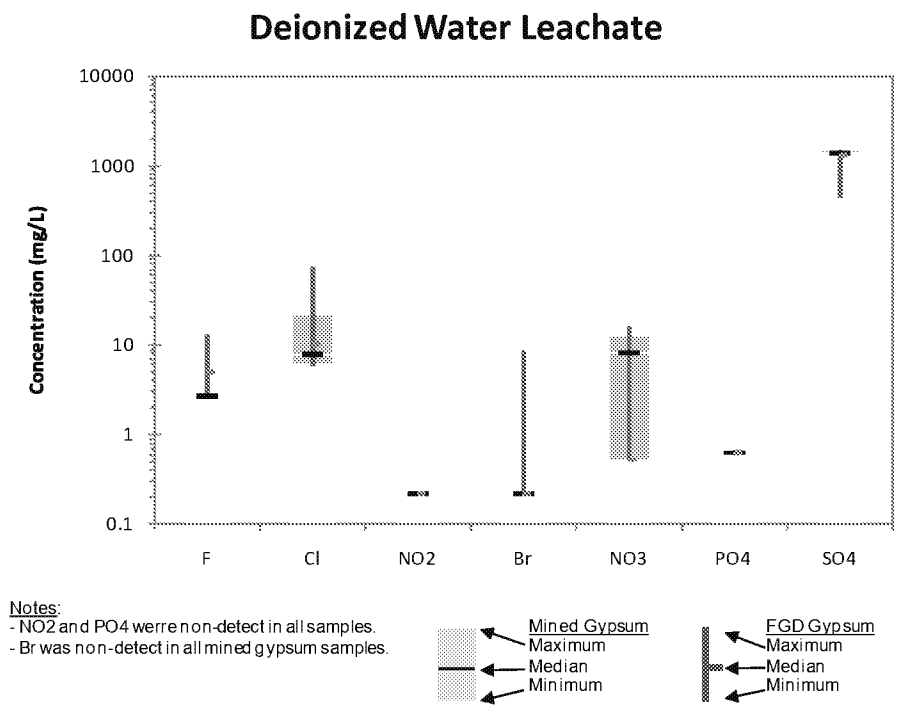


Figure 5-9
Comparison of DI water extract concentrations for FGD and mined gypsum

Table 5-11
Statistical Comparison of FGD and Mined Gypsum Leachate Samples

	Count		Variance	FGD Gypsum Median (mg/L)	Mined Gypsum Median (mg/L)
	FGD Gypsum	Mined Gypsum			
Al	32	11	not equal	0.16	0.13
As	32	11	all ND	<0.0050	<0.0050
B	32	11	equal	**0.19**	*<0.008*
Ba	32	11	equal	**0.027**	*0.022*
Be	32	11	equal	*<0.00061*	**0.00066**
Br	31	11	equal	**<0.22**	*<0.22*
Ca	32	11	not equal	**672**	*654*
Cd	32	11	equal	**0.00013**	*<0.00001*
Cl	31	11	not equal	10	7.7
Co	32	11	not equal	**0.0079**	*0.0060*
Cr	32	11	equal	**0.00018**	*0.00013*
Cu	32	11	equal	0.0013	0.0012
F	31	11	not equal	**4.9**	*2.7*
Fe	32	11	equal	0.0018	0.0019
Hg	31	11	not equal	**0.000063**	*<0.000015*
K	32	11	equal	*0.57*	**2.5**
Mg	32	11	not equal	2.1	1.2
Mn	32	11	equal	**0.026**	*0.008*
Mo	32	11	equal	0.0025	0.0034
Na	32	11	equal	*0.62*	**3.7**
Ni	32	11	equal	0.00023	0.00031
NO_2	31	11	all ND	<0.22	<0.22
NO_3	31	11	equal	*<0.53*	**8.1**
P	32	11	not equal	**0.056**	*<0.010*
Pb	32	11	equal	0.00010	0.00012
PO_4	31	11	all ND	<0.63	<0.63
S	32	11	not equal	521	520
Sb	32	11	equal	*0.00021*	**0.00041**
Se	32	10	equal	**0.014**	*<0.002*
SO_4	32	11	equal	*1,300*	**1,390**
Sr	32	11	not equal	*0.55*	**9.9**
Tl	32	11	equal	<0.000024	<0.000024
V	32	11	equal	0.00036	0.00061
Zn	32	11	equal	0.0045	0.0039

Explanation for Comparison of Datasets:

- **Bold shade** indicates a median from a dataset with statistically significant higher concentration range than the *italicized* median based on statistical analysis if the variances are equal or graphical analysis if the variances are not equal, as described in Appendix C.
- No formatting indicates that there is no statistical difference between the datasets if the variances are equal, and that the ranges are overlapping or within if the variances are not equal (see Appendix C).

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CONCLUSIONS

- The FGD gypsum is relatively pure calcium sulfate. The 32 samples analyzed were all greater than 90% calcium sulfate dihydrate. Median Ca and S concentrations in the FGD gypsum were 23.7% and 18.8%, respectively. Median concentrations for all other constituents were less than 0.1%.
- None of the 32 FGD gypsum samples had a TCLP leach test concentration that exceeded a TC limit. The maximum TCLP concentrations for 7 of the 8 RCRA metals in the 32 samples—Ag, As, Ba, Cd, Cr, Hg, and Pb—were two orders of magnitude or more lower than the TC limit. The maximum Se concentration was approximately one-half the TC limit.
- As would be expected, Ca and SO_4 had the highest concentrations (median > 500 mg/L) in SPLP leach tests on FGD gypsum. Among the trace metals, As was not detected in any samples (DL = 0.005 mg/L), and Be and Tl were detected in fewer than half of the samples. The highest trace metal concentrations were observed for Sr, B, and Al.
- The most notable power plant process affecting both total composition and leachate concentrations of the FGD gypsum was washing, which significantly reduced both total and leachable concentrations for many constituents.
- Comparison of FGD gypsum to mined gypsum samples demonstrated that FGD gypsum often had total and leachate concentrations similar to or lower than mined gypsum, specifically:
    - 19 of the 29 constituents analyzed for total composition had statistically similar or lower concentration in FGD gypsum compared to mined gypsum. Constituents in FGD gypsum with highest concentrations relative to mined gypsum were Hg and Se.
    - 22 of the 34 constituents analyzed for SPLP leachate concentration had statistically similar or lower concentration in FGD gypsum compared to mined gypsum. The constituents in the FGD gypsum extracts with the highest concentrations relative to the mined gypsum extracts were B, Hg, and Se, although the median concentrations of these constituents were relatively low.

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A
SAMPLE PLANT INFORMATION FORM AND TABLES

Plant Name:

Sample Date:

Unit #:	**Unit Capacity (MW):**
Unit Type • Pulverized Coal • Cyclone • FBC • Other (specify)	**Coal** • Bituminous • Subbituminous • Lignite • Blend (specify) • Sulfur (Low <1%, Med 1-3%, High >3%) Region/State(s):
NOx Control • Low-NOx burner • SCR • SNCR • None • Other (specify)	**Particulate Control** • ESP (hot-side) • ESP (cold-side) • Fabric filter • Other (specify)
SO3 Control • Fuel additives • Furnace injection • Duct injection • Wet ESP • None • Other (specify) Additive/Sorbent:	**SO2 Control** • Wet (forced, natural, inhibited) • Spray dryer • FBC • Furnace injection • Duct injection • None • Other (specify) Sorbent: Additive (DBA, Formic Acid):

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Mercury Control	**Miscellaneous**
• Sorbent injection • Furnace injection • Toxecon/Toxecon II • Fuel additives • Absorber additives • Wet ESP • None • Other (specify) Additive/Sorbent:	Flue gas conditioning:

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Table A-1
FGD Gypsum Sample Details

NRT SN	Plant ID	Unit	Volume of Material Collected (gallons)	Date Collected	Type of Material Collected	Collected off-belt or off-pile	Covered?	Washed or Unwashed	Homo-genized on- or off- site	Sampled by:	Comments
213	**06191**	1&2	25	7/3/08	FGD Gypsum	Off-belt	Unknown, not weathered	Unwashed	Off-site	Plant	Collected by plant personnel and shipped to NRT. Texture: light brown, very fine crystals, 5% soft lumps
216	**50207**	1&2	20	6/9/08	FGD Gypsum	Off-pile	Covered, not weathered	Washed	On-site	NRT	Pile was located inside a building, protected from the elements. Collected from the older end of the pile to avoid being directly under the conveyor while it was dumping. Texture: tan, very fine crystals, 10% soft lumps
223	**10165**	1-4	25	7/17/08	FGD Gypsum	Off-belt	Covered, not weathered	Washed	Off-site	NRT	Texture: grayish tan, very fine crystals, 5% soft lumps
224	**10164**	3	25	7/17/08	FGD Gypsum	Off-belt	Covered, not weathered	Washed	Off-site	NRT	Collected from a fresh pile just below the conveyor belt in a storage shed. Texture: tan, very fine crystals, soft lumps

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Table A-1 (continued)
FGD Gypsum Sample Details

NRT SN	Plant ID	Unit	Volume of Material Collected (gallons)	Date Collected	Type of Material Collected	Collected off-belt or off-pile	Covered?	Washed or Unwashed	Homo-genized on- or off- site	Sampled by:	Comments
225	**10172**	1	25	7/17/08	FGD Gypsum	Off-pile	Exposed, weathered	Unwashed*	Off-site	NRT	Plant relies on rainwater to wash gypsum prior to reuse. Sample collected from old pile (i.e., "washed"). Texture: gray, very fine crystals, 5% hard lumps, 5% sand-sized dark spots
226	**01159**	8-10	25	8/13/08	FGD Gypsum	Off-pile	Exposed, weathered	Unwashed*	On-site	Plant	Gypsum is sluiced to an impoundment and drained prior to reuse. Plant stockpiled some gypsum to the side of the impoundment for sample collection. Texture: gray, very fine crystals, 10% soft-hard lumps
227	**42197**	1&2	20	7/29/08	FGD Gypsum	Off-belt	Covered, not weathered	Washed	Off-site	NRT	Collected from a fresh pile located just below the belt in a storage shed. Texture: grayish tan, very fine "flakey" crystals, 10% soft lumps
228	**17202**	3	25	7/29/08	FGD Gypsum	Off-pile	Exposed, weathered	Unwashed*	Off-site	NRT	Collected from an impoundment, sample scraped off the top, lower material was very hard. Texture: tan, very fine crystals, 10% soft lumps, 5% dark colored sand-sized spots
229	**42197**	1&2	20	7/29/08	FGD Gypsum	Off-pile	Exposed, weathered	Washed	Off-site	NRT	Collected off a relatively fresh pile located on an ash impoundment. Texture: grayish tan, very fine "flakey" crystals, 10% soft lumps, 5% dark colored sand-sized spots

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Table A-1 (continued)
FGD Gypsum Sample Details

NRT SN	Plant ID	Unit	Volume of Material Collected (gallons)	Date Collected	Type of Material Collected	Collected off-belt or off-pile	Covered?	Washed or Unwashed	Homo-genized on- or off- site	Sampled by:	Comments
230	**35406**	1&2	15	7/24/08	FGD Gypsum	Off-pile	Covered, not weathered	Washed	Off-site	Plant	Collected by plant personnel and shipped to NRT. Texture: tan, very fine crystals
231	**33446**	1&2	15	8/25/08	FGD Gypsum	Off-belt	Covered, not weathered	Washed	Off-site	NRT	Texture: tan, very fine crystals, 10% soft lumps
232	**33102**	1&2	15	8/25/08	FGD Gypsum	Off-pile	Exposed, not weathered	Washed	Off-site	NRT	Pile was a couple days old, no rain. Texture: gray, very fine crystals, 10% soft lumps
233	**33107**	1-4	15	8/26/08	FGD Gypsum	Off-pile	Exposed, weathered	Washed	Off-site	NRT	Texture: gray, very fine crystals, 5% soft lumps
234	**14088**	2	15	9/8/08	FGD Gypsum	Off-belt	Exposed, not weathered	Washed	Off-site	NRT	Collected from new pile just below conveyor. Texture: tan, very fine crystals, 5% soft lumps
235	**14090**	5	12	9/8/08	FGD Gypsum	Off-belt	n/a, not weathered	Unwashed	Off-site	NRT	Collected directly from drum filter. Texture: tan, very fine crystals, 30% soft lumps, sulfur odor
237	**14061**	1&2	15	9/8/08	FGD Gypsum	Off-belt	Covered, not weathered	Washed	Off-site	NRT	Texture: white, very fine crystals, 10% soft lumps
238	**17154**	1-4	15	9/9/08	FGD Gypsum	Off-belt	Exposed, not weathered	Washed	Off-site	NRT	Collected from fresh pile just below conveyor as it was operating. Texture: light tan, very fine crystals, 10% soft lumps

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Table A-1 (continued)
FGD Gypsum Sample Details

NRT SN	Plant ID	Unit	Volume of Material Collected (gallons)	Date Collected	Type of Material Collected	Collected off-belt or off-pile	Covered?	Washed or Unwashed	Homo-genized on- or off- site	Sampled by:	Comments
239	**17155**	1	15	9/9/08	FGD Gypsum	Off-pile	Covered, not weathered	Washed	Off-site	NRT	Collected from day-old pile in shed, could not get fresh because hydroclone was restarting. Texture: tan, very fine crystals, 10% soft lumps, trace sand-sized dark spots
240	**17149**	1, 3, 4	15	9/9/08	FGD Gypsum	Off-pile	Covered, not weathered	Washed	Off-site	NRT	Collected from pile because system had not been running stably. Texture: light tan, very fine crystals, 5% soft lumps
244	**35085**	7&8	15	9/10/08	FGD Gypsum	Off-pile	Covered, not weathered	Washed	Off-site	NRT	Texture: tan, very fine crystals, 10% soft lumps
245	**35086**	1	15	9/10/08	FGD Gypsum	Off-pile	Exposed, not weathered	Washed	Off-site	NRT	Pile was approximately one day old. Texture: white, very fine "flakey" crystals, 5% soft lumps
247	**38131**	1-3	15	9/9/08	FGD Gypsum	Off-belt	Covered, not weathered	Washed	Off-site	NRT	Texture: white, very fine "flakey" crystals
248	**49022**	1&2	15	9/9/08	FGD Gypsum	Off-belt	Covered, not weathered	Washed	Off-site	NRT	Gypsum was collected from fresh side of the pile (near off-belt condition). Texture: tan, very fine crystals, 5% soft lumps

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Table A-1 (continued)
FGD Gypsum Sample Details

NRT SN	Plant ID	Unit	Volume of Material Collected (gallons)	Date Collected	Type of Material Collected	Collected off-belt or off-pile	Covered?	Washed or Unwashed	Homo-genized on- or off- site	Sampled by:	Comments
251	**49005**	1	15	9/10/08	FGD Gypsum	Off-pile	Exposed, weathered	Unwashed	Off-site	NRT	Plant contact mentioned that they use a type of limestone that doesn't yield marketable gypsum so all of it is landfilled. Texture: tan, very fine crystals, 10% soft lumps
253	**14090**	1-3	15	9/8/08	FGD Gypsum	Off-belt	Exposed, not weathered	Washed	Off-site	NRT	Collected from fresh pile just below conveyor, fresh cut was exposed in the pile using a front end loader. Texture: tan, very fine "flakey" crystals, 5% soft lumps
255	**38131**	1-3	15	9/9/08	FGD Gypsum	Off-pile	Covered, not weathered	Washed	Off-site	NRT	Non-spec material that is too wet is stored in a shed and allowed to dry, then is mixed with spec material for reuse; no way to tell how old the sample was. Texture: white, very fine "flakey" crystals, trace dark spots
260	**13612**		0.25	9/1/08	FGD Gypsum	Unknown	Unknown	Unknown	On-site	Plant	Plant personnel sent a single quart baggie of gypsum to NRT, and this material was forwarded "as is" to the lab. The exact collection date is unknown. Texture: tan, very fine crystals, no lumps

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Table A-1 (continued)
FGD Gypsum Sample Details

NRT SN	Plant ID	Unit	Volume of Material Collected (gallons)	Date Collected	Type of Material Collected	Collected off-belt or off-pile	Covered?	Washed or Unwashed	Homo-genized on- or off- site	Sampled by:	Comments
269	**43372**	1-3	15	11/4/08	FGD Gypsum	Off-belt	n/a, not weathered	Unwashed	On-site	NRT	Unwashed gypsum off drum filter; the conveyor belt for washing the gypsum was not operational during site visit. Texture: tan, very fine crystals, 10% soft clumps
270	**03587**	1-3	15	11/5/08	FGD Gypsum	Off-belt	Covered, not weathered	Unwashed	On-site	NRT	Collected from a fresh pile just below the conveyor belt in a storage shed. Texture: tan, very fine crystals, 5% soft lumps
296	**35015**	7	5	10/19/09	FGD Gypsum	Unknown	Unknown	Unknown	On-site	Plant	
298	**33106**		5	10/15/09	FGD Gypsum	Unknown	Unknown	Unknown	On-site	Plant	
304	**49003**		5	10/23/09	FGD Gypsum	Unknown	Unknown	Unknown	On-site	Plant	

*: see comments for further details
n/a: not applicable

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Table A-2
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
213	06191	1	250-500	Pul. Coal	Sub.	--	--	Low-NOx burner	Fabric Filter	--	None	*n/a*	--
		2	250-500	Pul. Coal	Sub.	--	--	Low-NOx burner	Fabric Filter	--	None	*n/a*	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	--	--	None	*n/a*	Converted from natural to forced oxidation in 2005	--
2	Wet, Forced	Limestone	--	--	None	*n/a*		--

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
216	50207	1	500-750	Pul. Coal	Sub.	Powder River Basin	< 1	SCR	ESP (cold-side)	Limestone slurry	None	*n/a*	SCR catalyst converts SO2 to SO3 without additives
		2	500-750	Pul. Coal	Sub.	Powder River Basin	< 1	SCR	ESP (cold-side)	Limestone slurry	None	*n/a*	SCR catalyst converts SO2 to SO3 without additives

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	--	--	None	*n/a*	Scrubber on-line same as SCR (11/2006)	Flue gas conditioning: limestone is milled on-site and mixed into slurry, limestone slurry is sprayed in absorber, slurry then transported to hydroclone and processed as either gypsum or filter cake.
2	Wet, Forced	Limestone	--	--	None	*n/a*	Scrubber on-line 4/2007	

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
223	10165	1	<250	Pul. Coal	Bit.	Central & Southern App. (VA, TN, AL)	1.32	Low-NOx Burner	ESP (cold-side)	SO3	None	*n/a*	--
		2	<250	Pul. Coal	Bit.	Central & Southern App. (VA, TN, AL)	1.32	Low-NOx Burner	ESP (cold-side)	SO3	None	*n/a*	--
		3	<250	Pul. Coal	Bit.	Central & Southern App. (VA, TN, AL)	1.32	Low-NOx Burner	ESP (cold-side)	SO3	None	*n/a*	--
		4	500-750	Pul. Coal	Bit.	Central & Southern App. (VA, TN, AL)	1.32	Low-NOx Burner + OFA + SCR	ESP (cold-side)	SO3	None	*n/a*	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	--	--	None	*n/a*	--	--
2	Wet, Forced	Limestone	--	--	None	*n/a*	--	--
3	Wet, Forced	Limestone	--	--	None	*n/a*	--	--
4	Wet, Forced	Limestone	--	--	None	*n/a*	--	--

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
224	10164	3	750-1000	Pul. Coal	Bit.	Central App. (KY, WV)	1.06	SCR + LNCFS II	ESP (cold-side)	NH3, SO3	Other	Lime + NH3	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
3	Wet, Forced	Limestone	--	--	None	*n/a*	--	--

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
225	10172	1	<250	Pul. Coal	Bit.	Southern App. (AL)	1.35	Low-NOx burner w/ gas co-fire	ESP (cold-side)	None	None	*n/a*	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	--	--	Sorbent injection, absorber additives	Activated carbon	Research and development testing of ACI, oxidizing agents	--

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
226	01159	8	<250	Pul. Coal	Bit.	Alabama	1.35	LNCFS II	ESP (hot-side)	None	None	*n/a*	--
		9	<250	Pul. Coal	Bit.	Alabama	1.35	CCOFA/SOFA	ESP (hot-side)	None	None	*n/a*	--
		10	500-750	Pul. Coal	Bit.	Alabama	1.35	LNCFS II, SCR	ESP (cold-side)	SO3	None	*n/a*	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
8	Wet, Forced	Limestone	--	--	None	*n/a*	--	--
9	Wet, Forced	Limestone	--	--	None	*n/a*	--	--
10	Wet, Forced	Limestone	--	--	None	*n/a*	--	--

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
227 & 229	42197	1	>1000	Pul. Coal	Bit.	Illinois Basin, Northern App.	2.59 - 2.9	Low-NOx burner, SCR	ESP (cold-side)	None	Duct Injection	Hydrated Lime	After air pre-heaters
		2	>1000	Pul. Coal	Bit.	Illinois Basin, Northern App.	2.59 - 2.9	Low-NOx burner, SCR	ESP (cold-side)	None	Duct Injection	Hydrated Lime	After air pre-heaters

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	None	--	Co-benefit control with SCR/FGD	--	--	--
2	Wet, Forced	Limestone	None	--	Co-benefit control with SCR/FGD	--	--	--

ED_005285_00000283-00282

Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
228	17202	3	>1000	Cyclone	Bit.	Illinois Basin	2.86	Low-NOx burner, SCR	ESP (cold-side)	None	Other	Hydrated Lime	Starting in 2010 on all 3 units. Injection point prior to scrubbers

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
3	Wet, Forced	Limestone	None	--	Co-benefit control with SCR/FGD	None	Plan to go to 70% PRB/ 30% ILB blend of coal on Unit 3 or 20% blend across all units in Fall 2008	--

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
230	35406	1	500-750	Pul. Coal	Bit.	--	--	Low-NOx burner, SCR	ESP (cold-side)	--	Duct Injection	Trona	Inject after SCR and air heater, before the ESP
		2	500-750	Pul. Coal	Bit.	--	--	Low-NOx burner, SCR	ESP (cold-side)	--	Duct Injection	Trona	Inject after SCR and air heater, before the ESP

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	--	--	None	*n/a*	--	--
2	Wet, Forced	Limestone	--	--	None	*n/a*	--	--

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
231	33446	1	<250	Pul. Coal	Bit.	Central App. (KY,VA, WV)	0.8 - 1.8	Low-NOx burner, SCR	ESP (cold-side)	None	Duct injection	Ammonia	Units have ability to inject ammonia but have not yet needed SO3 mitigation, so no injection as of sample date.
		2	<250	Pul. Coal	Bit.	Central App. (KY,VA, WV)	0.8 - 1.8	Low-NOx burner, SCR	ESP (cold-side)	None	Duct injection	Ammonia	

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	None	--	See *Management Method*	*n/a*	Installed Hg stack monitors to evaluate emissions for possible Hg air regulation.	Gypsum from scrubber removed by centrifuge for sale/recycle. Slurry too thin for removal from centrifugation is chemically treated with metclear and a polymer to allow precipitation of particulates with Hg attached. Sludge is pressed and sent to landfill.
2	Wet, Forced	Limestone	None	--	See *Management Method*	*n/a*		

ED_005285_00000283-00284

Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
232	33102	1	1150	Pul. Coal	Bit.	Southern App.	2.0	Low-NOx burner, SCR	ESP (cold-side)	SO3	Duct injection	--	--
		2	1150	Pul. Coal	Bit.	Southern App.	2.0	Low-NOx burner, SCR	ESP (cold-side)	SO3	Duct injection	--	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	Ability to use DBA (not using)	--	None	*n/a*	Each stack has two absorbers. Conveyors out to yard, open air stockpile.	Most gypsum is sold for wallboard. Some gypsum is landfilled, filter cake sludge is also landfilled.
2	Wet, Forced	Limestone	Ability to use DBA (not using)	--	None	*n/a*		

ED_005285_00000283-00285

Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
233	33107	1	250-500	Pul. Coal	Bit.	Central App.	2.4	Low-NOx burner, SNCR	ESP (cold-side)	--	Duct Injection	--	After air pre-heater, not very active.
		2	250-500	Pul. Coal	Bit.	Central App.	2.4	Low-NOx burner, SNCR	ESP (cold-side)	--	Duct Injection	--	After air pre-heater, not very active.
		3	500-750	Pul. Coal	Bit.	65% Central App., 35% Northern App.	2.5	Low-NOx burner, SNCR (SCR to be added to Unit 3 later 2008)	ESP (cold-side)	--	Duct Injection	--	--
		4	500-750	Pul. Coal	Bit.	65% Central App., 35% Northern App.	2.5	Low-NOx burner, SNCR	ESP (cold-side)	--	Duct Injection	--	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet	Limestone	Ability to use DBA (not using)	--	--	--	All units managed together. All four units have been running for a while.	One absorber for Units 1 and 2.
2	Wet	Limestone	Ability to use DBA (not using)	--	--	--		
3	Wet	Limestone	Ability to use DBA (not using)	--	--	--		Units 3 and 4 each have their own absorber.
4	Wet	Limestone	Ability to use DBA (not using)	--	--	--		

ED_005285_00000283-00286

Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
234	14088	2	500-750	Pul. Coal	Bit.	Indiana and Illinois	2.8	Low-NOx burner	ESP (cold-side)	--	None	*n/a*	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
2	Wet, Forced	Limestone	--	--	None	*n/a*	Second unit scrubber to be online by end of November 2008	--

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
235	14090	5	500-750	Pul. Coal	Bit.	Illinois Basin	High	Low-NOx burner, SCR (ammonia)	ESP (cold-side)	--	Duct injection	Sodium carbonate	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
5	Wet, Forced	Limestone	DBA	Yes, closed loop	None	*n/a*	DBA was used when sample was collected. Recently switched to sodium formate	In Unit 5, gypsum is dewatered with a vacuum filter drum; it is not washed. Dewatered gypsum (10%) is landfilled

ED_005285_00000283-00287

Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
237	14061	1	250-500	Pul. Coal	Bit.	Indiana	5.7	Low-NOx burner	ESP (cold-side)	--	None	*n/a*	--
		2	250-500	Pul. Coal	Bit.	Indiana	5.7	Low-NOx burner, SCR	ESP (cold-side)	--	None	*n/a*	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	Sodium formate when needed	--	None	*n/a*	--	--
2	Wet, Forced	Limestone	Sodium formate when needed	--	None	*n/a*	--	--

ED_005285_00000283-00288

Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
238	17154	1	250-500	Pul. Coal	Bit.	Illinois Basin	3.41	Low-NOx burner	ESP (cold-side)	None	None	*n/a*	--
		2	250-500	Pul. Coal	Bit.	Illinois Basin	3.41	Low-NOx burner	ESP (cold-side)	None	None	*n/a*	--
		3	250-500	Pul. Coal	Bit.	Illinois Basin	3.41	Low-NOx burner, SCR	ESP (cold-side)	None	None	*n/a*	--
		4	500-750	Pul. Coal	Bit.	Illinois Basin	3.41	Low-NOx burner, SCR	ESP (cold-side)	None	None	*n/a*	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	None	Yes, 75%+	None	*n/a*	Sample contains gypsum from all four units. No indication that DBA was not used in Unit 3. Converted from inhibited to forced oxidation in 1997.	All four units have a hydroclone. Blowdown goes to ash ponds, solids concentrated to 40% and pumped to common tank. Gypsum is washed using cooling tower hot-side blowdown
2	Wet, Forced	Limestone	None	Yes, 75%+	None	*n/a*		
3	Wet, Forced	Limestone	DBA	Yes, 75%+	None	*n/a*		
4	Wet, Forced	Limestone	None	Yes, 75%+	None	*n/a*		

ED_005285_00000283-00289

Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
239	17155	1	500-750	Pul. Coal	Bit.	Illinois Basin	3.2	Low-NOx burner, SCR	ESP (cold-side)	None	Duct injection	Hydrated Lime	High-surface hydrated lime

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	None	No, see comments	None	*n/a*	Water in scrubber comes from the ash pond, which receives off-spec & unused gypsum.	Hydrocloned to a vacuum belt filter, washed with water, and trucked to a wallboard plant (when market exists).

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
240	17149	1	500-750	Pul. Coal	Bit.	Illinois Basin	2.69	Low-NOx burner, SCR	ESP (cold-side)	--	--	--	--
		3	500-750	Pul. Coal	Bit.	Illinois Basin	2.69	Low-NOx burner, SCR	ESP (hot-side)	Trona	Duct injection	Trona	--
		4	500-750	Pul. Coal	Bit.	Illinois Basin	2.69	Low-NOx burner, SCR	ESP (hot-side)	Trona	Duct injection	Trona	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	--	Yes	None	*n/a*		Approximately 2/3 sent to wallboard plant, remainder stored on-site in lined impoundment
3	Wet, Forced	Limestone	--	No	None	*n/a*		
4	Wet, Forced	Limestone	--	No	None	*n/a*		

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
244	35085	7	500-750	Pul. Coal	Bit.	--	--	Low-NOx burner, SCR	ESP (cold-side)	--	Duct injection	Lime	Lime injected before scrubber
		8	500-750	Pul. Coal	Bit.	--	--	Low-NOx burner, SCR	ESP (cold-side)	--	Duct injection	Lime	Lime injected before scrubber

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
7	Wet, Forced	Limestone	--	--	None	*n/a*	--	--
8	Wet, Forced	Limestone	--	--	None	*n/a*	--	--

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
245	35086	1	>1000	Pul. Coal	Bit.	No sole source, mostly IL and OH	0.45 to 0.6	SCR	ESP (cold-side)	--	Duct and Furnace injection	--	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Magnesium enhanced lime	None	Yes, closed loop	--	--	Sulfuric acid is sometimes added to the end of the FGD process for pH control. Converted from natural to forced oxidation in 2000.	All spec gypsum must be sold to a wallboard manufacturer, non-spec goes out for agricultural use (have a permit with the state agency).

ED_005285_00000283-00291

Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
247 & 255	38131	1	750-1000	Pul. Coal	Bit.	Eastern	3.2	Low-NOx burner, SCR	Wet Scrubber	None	Duct Injection	Sodium Sulfite	--
		2	750-1000	Pul. Coal	Bit.	Eastern	3.2	Low-NOx burner, SCR	Wet Scrubber	None	Duct Injection	Sodium Sulfite	--
		3	750-1000	Pul. Coal	Bit.	Eastern	3.2	Low-NOx burner, SCR	ESP (cold-side) - Unit 3 only	None	Duct Injection	Sodium Sulfite	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Natural	Thiosorbic Lime	Sodium Thiosulfate	Yes	Co-benefit of SCR and FGD	--	Sampled when all 3 units operating for a couple weeks, although Unit 2 not operating at full load. Most fly ash captured by the Unit 1 and 2 scrubbers is separated from the final product, which contains 2 to 4 percent ash by weight.	Calcium sulfite from FGD system is converted to gypsum in a separate plant. Gypsum used for wallboard production. Some gypsum stored on-site (typically off-spec, usually due to moisture).
2	Wet, Natural	Thiosorbic Lime	Sodium Thiosulfate	Yes	Co-benefit control with SCR/FGD	--		
3	Wet, Natural	Thiosorbic Lime	Sodium Thiosulfate	Yes	Co-benefit control with SCR/FGD	--		

ED_005285_00000283-00292

Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
248	49022	1	750-1000	Pul. Coal	Bit.	Eastern	2.8 - 3.0	Low-NOx burner, SCR	ESP (cold-side)	--	Duct Injection	Trona	Injection after SCR and air heater, but before the ESP
		2	750-1000	Pul. Coal	Bit.	Eastern	2.8 - 3.0	Low-NOx burner, SCR	ESP (cold-side)	--	Duct Injection	Trona	

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	None	--	None	*n/a*	--	--
2	Wet, Forced	Limestone	None	--	None	*n/a*	--	--

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
251	49005	1	>1000	Pul. Coal	85%Bit. 15%Sub.	WV / Powder River Basin	--	Low-NOx burner, SCR	ESP (cold-side)	--	Duct Injection	Trona	Injection after SCR and air heater, but before the ESP

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	--	--	None	*n/a*	--	All gypsum goes to landfill; plant doesn't produce gypsum favorable for reuse/sale.

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
253	14090	1	500-750	Pul. Coal	Bit.	Illinois Basin	High	Low-NOx burner, SCR (ammonia)	ESP (cold-side)	--	Duct injection	Sodium carbonate	--
		2	500-750	Pul. Coal	Bit.	Illinois Basin	High	Low-NOx burner, SCR (ammonia)	ESP (cold-side)	--	Duct injection	Sodium carbonate	--
		3	500-750	Pul. Coal	Bit.	Illinois Basin	High	Low-NOx burner, SCR (ammonia)	ESP (cold-side)	--	Duct injection	Sodium carbonate	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	None	Yes, closed loop	None	*n/a*	--	In Units 1-3, gypsum is dewatered at one large facility with a primary hydroclone, further dewatered on vacuum belt, and washed. Dewatered gypsum (10%) is landfilled
2	Wet, Forced	Limestone	None	Yes, closed loop	None	*n/a*	--	
3	Wet, Forced	Limestone	None	Yes, closed loop	None	*n/a*	--	

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
260	13612	--	--	Pul. Coal	Bit.	Illinois Basin	--	SCR	ESP (cold-side)	--	--	--	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
--	Wet, Forced	Limestone	--	--	None	*n/a*	--	--

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
269	43372	1	750-1000	Pul. Coal	80%Lig. 20%PRB	East Texas	1.2	Low-NOx burner	ESP (cold-side)	--	None	*n/a*	--
		2	750-1000	Pul. Coal	80%Lig. 20%PRB	East Texas	1.2	Low-NOx burner	ESP (cold-side)	--	None	*n/a*	--
		3	750-1000	Pul. Coal	80%Lig. 20%PRB	East Texas	1.2	Low-NOx burner	ESP (cold-side)	--	None	*n/a*	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	DBA	No, Clarified water only	None	*n/a*	ACI planned for future mercury control. Converted from inhibited to forced oxidation in mid- to late 90s.	Scrubber blows down to thickener tanks and then to vacuum filters. Drum and belt are both used. Gypsum washed only when sending to market.
2	Wet, Forced	Limestone	DBA	No, Clarified water only	None	*n/a*		
3	Wet, Forced	Limestone	DBA	No, Clarified water only	None	*n/a*		

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
270	03587	1	750-1000	Pul. Coal	Bit.	Arizona	0.5	None	ESP (hot-side)	--	None	*n/a*	--
		2	750-1000	Pul. Coal	Bit.	Arizona	0.5	None	ESP (hot-side)	--	None	*n/a*	--
		3	750-1000	Pul. Coal	Bit.	Arizona	0.5	None	ESP (hot-side)	--	None	*n/a*	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
1	Wet, Forced	Limestone	--	No	None	*n/a*	--	The gypsum is dewatered via vacuum belt filter and subsequently co-managed in dry ash landfill.
2	Wet, Forced	Limestone	--	No	None	*n/a*	--	
3	Wet, Forced	Limestone	--	No	None	*n/a*	--	

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
296	35015	--	--	Pul. Coal	Bit.	--	--	--	ESP (cold-side)	--	--	--	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
--	Wet, Forced	--	--	--	--	--	--	--

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
298	33106	--	--	Pul. Coal	Bit.	--	--	--	ESP (cold-side)	--	--	--	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
--	Wet, Forced	--	--	--	--	--	--	--

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Table A-2 (Continued)
FGD Gypsum Sample Power Plant Details

NRT ID	Plant ID	Unit			Coal			NOx	Particulates		SO3		
		Unit #	Unit Cap. (MW)	Unit Type	Coal Type	Region/ states	Sulfur Cont. (%)	NOx Control	Particulate Control	Flue Gas Conditioning	SO3 Control	Additive/ Sorbent	Comments
304	49003	--	--	Pul. Coal	Bit.	--	--	--	ESP (cold-side)	--	--	--	--

Unit #	SO2				Mercury		Comments	Management Method
	SO2 Control	Sorbent	Additive	Recycle	Mercury Control	Additive/ Sorbent		
--	Wet, Forced	--	--	--	--	--	--	--

--: Information not available
n/a: not applicable

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B
DATA TABLES

Total Composition - FGD Gypsum

Sample	213	216	223	224	225	226	226 Rep	227	228	229	230	231
Al (mg/kg)	1,360	99	310	230	928	335	674	91	142	116	138	356
As (mg/kg)	3.6	2.1	3.1	4.1	7.4	11	13	2.2	3.2	2.2	3.6	2.8
B (mg/kg)	387	5.6	6.5	4.9	23	46	78	6.7	44	2.7	13	14
Ba (mg/kg)	33	5.1	2.4	6.4	18	8.6	12	7.6	19	8.5	13	5.8
Be (mg/kg)	0.056	<0.010	0.027	0.059	0.11	0.038	<0.10	0.031	0.034	0.025	0.012	0.011
Ca (mg/kg)	230,000	249,000	228,000	230,000	252,000	224,000	184,000	216,000	226,000	214,000	265,000	240,000
Cd (mg/kg)	0.082	0.045	0.37	0.10	0.15	0.017	<0.040	0.088	0.24	0.17	0.072	0.031
Co (mg/kg)	0.54	<0.17	<0.17	0.23	0.62	0.45	0.54	<0.17	0.22	<0.17	0.23	0.46
Cr (mg/kg)	5.4	1.0	2.8	2.7	8.7	1.0	1.6	2.0	2.2	1.9	2.5	1.8
Cu (mg/kg)	1.7	1.2	0.75	0.94	2.5	1.5	1.4	0.61	0.91	0.51	1.3	1.9
Fe (mg/kg)	1,770	641	304	277	1,245	791	701	262	635	315	808	1,060
Hg (mg/kg)	0.16	0.94	0.89	0.12	0.33	1.4	0.94	0.078	0.41	0.17	0.42	0.046
K (mg/kg)	620	46	270	212	343	324	469	63	115	56	104	304
Li (mg/kg)	1.4	0.045	1.2	0.19	1.6	0.34	1.4	0.25	0.041	0.16	0.12	0.31
Mg (mg/kg)	2,680	1,350	414	562	616	1,439	1,680	1,940	2,040	3,060	1,800	238
Mn (mg/kg)	129	5.6	1.3	19	9.6	8.8	8.9	6.5	14	3.4	8.0	79
Mo (mg/kg)	0.61	0.32	0.19	0.81	2.5	0.54	0.89	0.37	1.3	0.19	0.52	0.43
Na (mg/kg)	1,300	53	11	10	50	29	58	15	20	18	22	19
Ni (mg/kg)	2.4	0.92	0.88	0.82	1.9	0.97	0.96	0.51	0.84	0.55	1.6	1.4
P (mg/kg)	179	18	25	24	58	21	25	36	48	54	33	126

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Sample	213	216	223	224	225	226	226 Rep	227	228	229	230	231
Pb (mg/kg)	0.88	0.71	0.71	1.1	1.7	0.76	0.88	0.53	1.1	<0.53	1.1	1.9
S (mg/kg)	188,000	200,000	184,000	183,000	200,000	169,000	150,000	170,000	164,000	163,000	205,000	194,000
Sb (mg/kg)	0.62	0.22	0.080	0.12	0.34	0.18	0.24	0.081	0.078	0.057	0.11	0.27
Se (mg/kg)	6.6	7.7	12	22	13	13	18	2.4	4.9	3.4	4.2	20
Si (mg/kg)	1,050	245	411	504	301	553	478	79	486	113	305	633
Sr (mg/kg)	97	100	220	183	213	115	95	233	183	208	167	88
Tl (mg/kg)	0.0080	0.0074	0.0068	0.023	0.029	0.040	0.022	0.015	0.024	0.021	0.013	0.0092
V (mg/kg)	8.6	0.92	2.0	1.6	5.3	1.6	2.9	1.2	1.9	1.6	1.6	0.70
Zn (mg/kg)	4.1	4.8	12	15	14	3.3	6.2	8.5	23	12	10	2.6

Sample	232	233	234	235	237	238	239	240	244	245	247	248
Al (mg/kg)	211	508	206	207	98	212	256	175	145	171	102	61
As (mg/kg)	10	2.1	2.6	3.9	2.5	2.9	3.5	2.6	2.7	2.0	2.8	2.9
B (mg/kg)	9.0	12	22	81	11	6.3	14	13	7.9	19	5.7	8.2
Ba (mg/kg)	3.0	3.4	10.0	5.7	5.9	13	9.2	6.1	12	2.7	3.2	6.1
Be (mg/kg)	0.022	0.054	<0.010	0.019	0.014	0.035	0.024	0.031	0.016	0.014	<0.010	<0.010
Ca (mg/kg)	233,000	229,000	249,000	250,000	268,000	259,000	248,000	232,000	252,000	253,000	208,000	243,000
Cd (mg/kg)	0.0082	0.0064	0.041	0.21	0.097	0.12	0.17	0.069	0.049	0.0058	0.011	0.034
Co (mg/kg)	0.20	0.22	0.23	0.37	0.19	0.31	0.32	0.25	0.22	<0.17	<0.17	0.18
Cr (mg/kg)	0.89	1.1	2.5	4.1	1.9	8.6	2.8	2.4	1.9	0.75	0.45	0.60
Cu (mg/kg)	0.66	0.76	1.3	2.4	0.84	1.5	1.6	1.6	0.89	0.40	0.88	0.84
Fe (mg/kg)	1,290	465	777	1,710	605	789	1,520	733	1,300	130	335	614
Hg (mg/kg)	0.65	0.19	0.0070	0.38	0.18	0.13	0.026	0.13	0.31	0.053	0.0090	0.66
K (mg/kg)	250	276	211	269	106	177	136	102	137	60	29	49
Li (mg/kg)	0.034	0.15	0.17	0.51	0.16	0.21	0.46	0.19	0.28	<0.016	<0.016	0.024
Mg (mg/kg)	488	592	70	5,860	1,830	1,090	1,730	791	691	210	50	593
Mn (mg/kg)	1.9	2.6	46	40	4.3	24	13	14	4.7	0.89	0.83	9.9
Mo (mg/kg)	0.33	0.15	0.28	2.0	0.25	0.64	3.1	0.58	0.52	0.044	0.085	0.32

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Sample	232	233	234	235	237	238	239	240	244	245	247	248
Na (mg/kg)	14	12	10	176	23	25	31	85	28	17	22	13
Ni (mg/kg)	0.70	0.88	1.2	2.4	0.76	1.3	1.5	1.2	1.1	0.25	<0.23	1.1
P (mg/kg)	25	14	22	48	25	34	40	31	31	4.5	8.6	33
Pb (mg/kg)	0.61	<0.53	0.92	1.2	<0.53	0.80	8.3	1.2	1.2	<0.53	1.5	1.1
S (mg/kg)	186,000	184,000	203,000	187,000	208,000	200,000	191,000	189,000	205,000	206,000	172,000	195,000
Sb (mg/kg)	0.057	0.063	0.084	0.21	0.13	5.0	0.69	0.17	0.13	0.12	0.079	1.00
Se (mg/kg)	32	7.0	9.3	3.5	3.9	4.6	3.8	4.6	2.6	1.6	1.5	9.5
Si (mg/kg)	228	167	260	262	200	386	222	234	228	101	69	217
Sr (mg/kg)	104	154	120	191	173	349	331	375	292	141	143	90
Tl (mg/kg)	0.013	0.0068	0.0016	0.010	0.014	<0.10	0.062	0.012	0.0056	<0.00070	0.0020	0.011
V (mg/kg)	0.67	0.99	1.2	2.1	1.1	2.4	3.2	2.0	1.6	0.32	0.48	1.3
Zn (mg/kg)	2.8	2.1	6.4	12	4.9	7.5	4.9	4.6	8.8	1.9	1.9	5.8

Sample	251	253	255	260	269	270	270 Rep	296	298	304
Al (mg/kg)	239	200	140	77	564	1,610	2,030	545	609	891
As (mg/kg)	3.3	3.5	2.4	2.6	2.5	4.9	3.6	3.3	7.3	2.3
B (mg/kg)	104	44	3.7	15	51	146	160	13	5.5	55
Ba (mg/kg)	27	5.1	3.8	0.91	9.6	55	68	4.3	6.4	22
Be (mg/kg)	<0.010	<0.010	<0.010	0.011	<0.010	0.13	0.11	0.088	<0.10	0.034
Ca (mg/kg)	263,000	240,000	213,000	243,000	246,000	233,000	190,000	200,000	209,000	199,000
Cd (mg/kg)	0.22	0.064	0.0072	0.044	0.046	0.094	0.12	0.056	0.017	0.23
Co (mg/kg)	0.42	0.20	0.20	0.24	0.28	0.72	0.84	0.50	0.37	0.51
Cr (mg/kg)	2.6	2.7	0.95	15	2.2	3.2	3.8	1.7	1.6	5.1
Cu (mg/kg)	1.9	1.1	0.25	0.98	1.0	3.2	4.5	1.9	2.7	2.3
Fe (mg/kg)	1,820	834	814	868	1,460	1,250	1,100	1,380	870	1,250
Hg (mg/kg)	0.36	0.26	0.035		0.55	0.052	0.040	0.48	0.19	0.32
K (mg/kg)	309	233	34	131	182	475	928	234	462	744
Li (mg/kg)	0.80	0.51	0.10	<0.016	0.26	0.81	1.8	0.62	0.53	2.0

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Sample	251	253	255	260	269	270	270 Rep	296	298	304
Mg (mg/kg)	2,880	2,790	81	1,080	1,050	2,830	2,930	2,580	309	2,350
Mn (mg/kg)	42	7.9	1.1	49	8.7	13	15	13	3.6	30
Mo (mg/kg)	0.69	1.3	0.11	0.63	0.69	0.95	1.3	0.77	0.74	0.85
Na (mg/kg)	119	81	64	15	327	1,200	1,490	48	14	93
Ni (mg/kg)	2.1	1.2	0.32	1.3	1.2	2.2	2.7	1.7	0.66	2.9
P (mg/kg)	47	40	11	127	14	50	52	32	25	50
Pb (mg/kg)	1.2	1.4	<0.53	1.7	0.74	2.0	1.7	0.87	0.76	1.0
S (mg/kg)	207,000	194,000	177.000	195,000	189,000	179,000	147,000	156,000	174,000	159,000
Sb (mg/kg)	0.90	0.16	0.051	2.0	0.34	0.32	0.23	0.14	0.13	0.24
Se (mg/kg)	4.5	3.5	1.4	4.0	28	26	28	6.1	17	5.6
Si (mg/kg)	428	318	99	185	406	542	213	96	335	140
Sr (mg/kg)	364	192	132	71	172	117	113	100	107	405
Tl (mg/kg)	0.011	0.0080	0.0058	0.016	0.011	0.030	0.011	0.015	0.0044	0.0054
V (mg/kg)	2.4	1.6	0.72	0.78	2.2	4.9	7.4	3.0	1.6	6.6
Zn (mg/kg)	15	6.4	2.8	4.2	1.8	5.9	9.0	9.6	4.4	19

ED_005285_00000283-00301

Total Composition - Mined Gypsum

Sample	279	281	283	285	287	287 Rep	289	291	293	295	301	303
Al (mg/kg)	1,260	143	2,420	192	1,330	1,380	1,950	1,700	2,160	2,020	851	208
As (mg/kg)	2.6	<1.6	2.0	<1.6	1.7	1.8	2.1	2.4	<1.6	2.3	<1.6	2.3
B (mg/kg)	8.4	8.0	15	11	7.5	7.5	4.2	13	5.5	26	6.5	7.8
Ba (mg/kg)	25	3.2	21	2.2	5.8	6.3	23	6.6	21	31	12	4.0
Be (mg/kg)	<0.010	<0.010	0.046	<0.010	0.013	<0.10	<0.10	<0.10	0.037	0.033	<0.010	<0.010
Ca (mg/kg)	265,000	203,000	211,000	173,000	200,000	201,000	232,000	230,000	211,000	227,000	213,000	258,000
Cd (mg/kg)	0.21	0.011	0.068	0.014	0.062	0.061	0.11	0.033	0.0074	0.040	0.041	<0.040
Co (mg/kg)	0.62	<0.17	0.61	0.27	0.86	0.92	2.1	0.82	0.85	1.1	0.32	0.28
Cr (mg/kg)	1.3	0.27	2.3	0.57	1.7	1.8	2.0	2.6	2.5	3.2	0.62	0.32
Cu (mg/kg)	0.78	1.9	0.69	0.76	1.1	1.3	4.1	2.0	4.7	2.4	1.1	3.2
Fe (mg/kg)	886	59	1,220	246	924	1,020	3,770	1,630	1,540	1,760	572	171
Hg (mg/kg)	0.0020	0.00045	0.00082	0.00030	0.00070	0.00084	0.0018	0.010	0.00049	0.015	0.00070	0.00072
K (mg/kg)	668	96	1,230	212	1,140	1,160	518	940	940	760	804	441
Li (mg/kg)	5.6	0.79	10	0.99	3.8	4.1	2.0	12	5.3	4.9	2.5	14
Mg (mg/kg)	1,040	500	15,200	15,600	830	907	977	3,900	3,650	5,010	879	2,990
Mn (mg/kg)	241	10	16	35	25	27	57	37	62	108	21	20
Mo (mg/kg)	1.3	0.34	1.0	0.65	0.59	0.53	1.2	1.2	0.37	1.1	0.42	0.74
Na (mg/kg)	49	73	419	356	39	41	246	113	73	172	168	29
Ni (mg/kg)	0.73	<0.23	2.0	0.93	2.0	2.3	1.8	2.1	1.7	2.3	0.39	0.45
P (mg/kg)	31	10	27	7.3	27	28	75	25	40	50	22	8.7
Pb (mg/kg)	2.1	<0.53	2.5	1.7	1.6	2.0	1.6	4.1	0.63	2.3	1.1	<0.53
S (mg/kg)	211,000	167,000	154,000	119,000	161,000	167,000	147,000	142,000	174,000	174,000	168,000	209,000
Sb (mg/kg)	0.24	0.44	1.2	0.27	0.20	0.29	1.2	0.45	0.41	0.41	0.44	0.52
Se (mg/kg)	0.35	0.12	0.23	0.11	0.12	0.13	0.15	<0.064	<0.064	0.24	<0.064	<0.064
Si (mg/kg)	151	200	194	166	209	190	153	142	205	167	168	100
Sr (mg/kg)	671	1,150	3,190	722	675	679	1,310	1,140	1,140	1,090	924	1,660
Tl (mg/kg)	0.20	<0.00070	0.0016	0.0018	0.12	0.0096	0.014	0.0084	0.0046	0.011	0.022	0.021

ED_005285_00000283-00302

Sample	279	281	283	285	287	287 Rep	289	291	293	295	301	303
V (mg/kg)	2.9	0.32	5.5	0.65	3.0	2.9	9.2	4.7	3.8	4.1	1.8	1.3
Zn (mg/kg)	23	1.6	6.9	3.7	16	16	6.9	2.7	5.7	6.2	16	1.4

ED_005285_00000283-00303

TCLP - FGD Gypsum

Sample	213	216	223	224	225	226	Replicate	227	228	229	230	231
Ag (mg/L)	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017
As (mg/L)	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	0.023	0.015	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Ba (mg/L)	0.062	0.037	0.048	0.047	0.059	0.043	0.047	0.028	0.022	0.017	0.024	0.022
Cd (mg/L)	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	0.0049	0.0057	<0.0037	<0.0037
Cr (mg/L)	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018
Hg (mg/L)	0.00011	0.000033	0.000055	0.000022	0.000096	0.000037	0.000070	0.000022	0.000018	0.000022	0.000018	0.000029
Pb (mg/L)	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062
Se (mg/L)	<0.089	<0.089	<0.089	0.10	0.14	0.16	0.15	<0.089	<0.089	<0.089	<0.089	0.090
EC (uS/cm)	16,100	15,000	15,100	15,400	16,800	15,400	15,200	19,300	15,200	15,300	14,900	14,500
pH (lab) (SU)	5.0	5.3	5.0	5.4	5.5	5.4	7.5	6.6	5.9	6.4	6.0	4.9
pH (final) (SU)	4.9	5.0	4.9	5.0	6.3	5.0	6.0	5.3	5.1	5.5	5.3	4.8

Sample	232	233	234	235	237	238	239	240	244	245	247	248
Ag (mg/L)	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017
As (mg/L)	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Ba (mg/L)	0.032	0.043	0.024	0.058	0.021	0.063	0.076	0.053	0.038	0.039	0.039	0.017
Cd (mg/L)	<0.0037	<0.0037	<0.0037	0.0082	<0.0037	0.0044	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037
Cr (mg/L)	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018
Hg (mg/L)	0.000022	0.000029	0.000018	0.000022	<0.000015	0.000018	0.000018	0.000018	0.000018	0.000018	<0.000015	0.000022
Pb (mg/L)	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062
Se (mg/L)	0.26	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089
EC (uS/cm)	15,200	15,300	14,300	17,000	15,400	16,100	16,000	15,300	14,300	14,000	14,400	18,500
pH (lab) (SU)	5.3	5.1	5.0	6.4	5.9	6.0	6.3	5.3	5.1	4.9	4.9	5.3
pH (final) (SU)	5.0	5.0	4.9	6.0	5.2	5.3	6.0	5.0	5.0	4.8	4.8	5.1

ED_005285_00000283-00304

Sample	251	253	255	260	269	270	Replicate	296	298	304
Ag (mg/L)	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017
As (mg/L)	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Ba (mg/L)	0.038	0.033	0.041	0.0098	0.079	0.079	0.078	0.047	0.042	0.054
Cd (mg/L)	0.0049	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	0.0052
Cr (mg/L)	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018
Hg (mg/L)	0.000022	0.000022	<0.000015		0.00058	0.000033	0.000026	0.000022	<0.000015	0.000018
Pb (mg/L)	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062
Se (mg/L)	<0.089	<0.089	<0.089	<0.089	0.45	0.26	0.39	<0.089	<0.089	<0.089
EC (uS/cm)	16,200	15,700	14,600		17,300	17,900	19,200	15,600	15,000	16,200
pH (lab) (SU)	5.6	5.7	4.9	5.4	6.4	7.2	7.6	7.3	5.0	6.4
pH (final) (SU)	5.3	5.1	4.8		6.3	6.3	6.2	5.7	4.9	5.5

ED_005285_00000283-00305

TCLP - Mined Gypsum

Sample	279	281	283	285	287	Replicate	289	291	293	295	301	303
Ag (mg/L)	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017	<0.017
As (mg/L)	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Ba (mg/L)	0.079	0.013	0.055	0.010	0.038	0.045	0.099	0.023	0.053	0.11	0.047	0.024
Cd (mg/L)	0.0059	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037
Cr (mg/L)	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018	<0.018
Hg (mg/L)	0.000015	0.000015	<0.000015	0.000015	0.000015	<0.000015	0.000015	0.000015	<0.000015	0.000018	<0.000015	<0.000015
Pb (mg/L)	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062	<0.062
Se (mg/L)	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089	<0.089
EC (uS/cm)	15,300	14,600	17,400	15,900	17,500	15,800	16,500	17,000	15,300	15,900	16,600	16,200
pH (lab) (SU)	5.4	5.0	6.4	6.7	5.4	5.3	6.9	7.5	5.6	7.0	6.4	6.5
pH (final) (SU)	5.3	4.9	5.9	5.4	5.1	5.1	6.3	5.7	5.0	5.7	5.9	5.2

ED_005285_00000283-00306

SPLP - FGD Gypsum

Sample	213	216	223	224	225	226	226.5	227	228	229	230	231
Al (mg/L)	0.12	0.19	0.13	0.19	0.21	0.18	0.18	0.17	0.15	0.13	0.16	0.16
As (mg/L)	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
B (mg/L)	20	<0.0078	0.15	<0.0078	0.17	2.8	<0.0078	<0.0078	1.5	<0.0078	0.16	<0.0078
Ba (mg/L)	0.043	0.025	0.034	0.027	0.040	0.034	0.034	0.018	0.015	0.0087	0.013	0.0089
Be (mg/L)	<0.00061	<0.00061	<0.00061	<0.00061	<0.00061	<0.00061	0.00069	<0.00061	<0.00061	<0.00061	0.00063	0.00066
Ca (mg/L)	702	659	668	672	680	677	672	665	666	655	701	666
Cd (mg/L)	0.00053	0.000023	0.00012	0.00022	0.00041	0.000075	0.000070	0.00027	0.00049	0.00021	0.000085	0.000010
Co (mg/L)	0.0079	0.0053	0.0024	0.0023	0.0024	0.0026	0.0066	0.0026	0.0026	0.0037	0.0087	0.0086
Cr (mg/L)	<0.000090	0.00016	0.00019	0.00017	0.00014	0.00024	<0.000090	0.00021	0.00013	0.00022	0.00024	0.00042
Cu (mg/L)	0.0021	0.0014	0.00055	0.00065	0.0016	0.00074	0.00094	0.0024	0.00060	0.00066	0.00090	0.0019
Fe (mg/L)	0.0018	0.0014	0.0012	0.0013	0.0014	0.0014	0.0072	0.016	0.0018	0.0020	0.013	0.0014
Hg (mg/L)	0.00035	0.00029	0.0010	0.00026	0.000026	0.00038	0.00034	0.000063	0.00037	0.000018	0.000029	0.000044
K (mg/L)	7.2	0.39	0.46	0.31	1.1	1.2	2.6	0.27	0.46	0.25	0.62	0.51
Mg (mg/L)	52	6.9	1.4	0.86	4.8	28	37	3.1	15	0.34	1.3	2.1
Mn (mg/L)	7.5	0.027	0.0030	0.017	0.012	0.14	0.037	0.022	0.026	0.0027	0.081	0.061
Mo (mg/L)	0.0086	0.0018	0.0012	0.0028	0.029	0.010	0.0091	0.0018	0.011	0.00055	0.0026	0.0024
Na (mg/L)	71	0.86	0.22	0.12	1.5	1.4	3.8	0.14	0.63	0.034	0.34	0.24
Ni (mg/L)	0.0094	0.00088	0.00017	0.00016	0.00024	0.00020	0.00048	0.00056	0.00064	0.00022	0.00035	0.00086
P (mg/L)	0.012	0.081	0.049	0.063	0.054	0.027	0.044	0.092	0.078	0.018	0.060	0.048
Pb (mg/L)	0.00012	0.00013	0.00015	0.00015	0.00015	0.00013	0.00035	0.00057	0.00016	0.00018	0.00010	0.000080
S (mg/L)	655	498	503	507	511	530	545	497	508	495	558	505
Sb (mg/L)	0.0010	0.0014	0.00037	0.00038	0.0012	0.00093	0.00067	0.00020	0.00018	0.00019	0.00016	0.000035
Se (mg/L)	0.075	0.014	0.0060	0.099	0.034	0.0066	0.0081	0.0076	0.016	0.011	0.0030	0.091
Sr (mg/L)	0.35	0.29	0.93	0.54	2.3	0.35	0.36	0.72	0.52	0.53	0.96	0.29
Tl (mg/L)	0.000080	<0.000024	<0.000024	0.00074	<0.000024	<0.000024	0.00030	<0.000024	<0.000024	<0.000024	0.000030	<0.000024
V (mg/L)	0.0033	0.00024	0.00034	0.00077	0.0021	0.0020	0.0014	0.00056	0.00066	0.00072	0.00022	<0.000080
Zn (mg/L)	0.0043	0.0067	0.0016	0.0058	0.0018	<0.00061	0.0060	0.0035	0.0031	0.0023	0.0077	0.0094

ED_005285_00000283-00307

Sample	213	216	223	224	225	226	226.5	227	228	229	230	231
EC (uS/cm)	8,270	6,280	6,350	5,020	6,230	6,460	6,520	6,300	5,120	6,040	6,210	6,180
pH (final) (SU)	10	9.9	9.0	8.8	8.7	8.7	7.7	8.5	8.6	8.4	8.3	8.0
pH (lab) (SU)	7.8	8.0	7.8	7.8	7.8	7.4	7.5	7.7	7.5	7.0	7.7	7.6

Sample	232	233	234	235	237	238	239	240	244	245	247	248
Al (mg/L)	0.14	0.17	0.17	0.18	0.12	0.17	0.18	0.16	0.078	0.16	0.12	0.076
As (mg/L)	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
B (mg/L)	<0.0078	<0.0078	<0.0078	4.6	0.36	0.17	0.14	0.28	0.34	0.22	0.21	0.50
Ba (mg/L)	0.024	0.028	0.017	0.030	0.016	0.035	0.038	0.034	0.024	0.018	0.030	0.011
Be (mg/L)	<0.00061	0.00071	<0.00061	0.00063	<0.00061	0.00061	<0.00061	0.00062	<0.00061	<0.00061	0.00063	<0.00061
Ca (mg/L)	667	671	676	665	724	702	777	698	658	658	722	678
Cd (mg/L)	<0.000010	<0.000010	0.00014	0.00038	0.00033	0.00027	0.00020	0.00027	<0.000010	0.000030	<0.000010	0.000010
Co (mg/L)	0.0085	0.0084	0.0088	0.0083	0.0085	0.0082	0.0081	0.0077	0.0077	0.0023	0.0099	0.0074
Cr (mg/L)	0.00012	0.00011	0.0011	0.00031	0.00018	0.00021	0.00018	0.00020	0.00018	0.00017	0.00020	0.00040
Cu (mg/L)	0.0014	0.0015	0.0013	0.0025	0.0012	0.00067	0.0010	0.0010	0.0016	0.0012	0.0011	0.0022
Fe (mg/L)	0.0016	0.0015	0.0023	0.0018	0.0020	0.0015	0.0015	0.0018	0.0018	0.011	0.0021	0.040
Hg (mg/L)	0.00036	0.000044	0.000018	0.000022	0.000018	0.00083	0.000018	0.00026	0.000018	0.00017	0.000018	0.000022
K (mg/L)	0.29	0.39	0.34	2.0	0.72	0.46	0.67	0.51	0.45	0.72	0.26	0.26
Mg (mg/L)	0.38	0.67	0.30	26	1.8	1.4	1.6	3.5	1.4	2.2	1.0	0.37
Mn (mg/L)	0.0044	0.0038	0.026	0.39	0.0055	0.012	0.016	0.033	0.0064	0.0018	0.0019	0.069
Mo (mg/L)	0.00096	0.00036	0.0015	0.026	0.0012	0.0022	0.022	0.0045	0.0021	0.00088	0.00089	0.00069
Na (mg/L)	0.11	0.078	0.24	9.6	0.41	0.53	0.60	3.2	0.53	0.41	0.79	0.25
Ni (mg/L)	<0.00010	<0.00010	0.00012	0.00083	0.00047	0.00011	<0.00010	<0.00010	<0.00010	0.00023	0.00019	0.00080
P (mg/L)	0.059	0.054	0.025	<0.0099	0.031	0.032	0.030	0.088	0.12	0.12	0.12	0.11
Pb (mg/L)	0.000065	0.000065	0.000075	0.000080	0.000065	0.000090	0.000070	0.000085	0.000090	0.00029	0.00012	0.0013
S (mg/L)	510	506	521	540	580	652	810	618	494	505	697	517
Sb (mg/L)	0.00025	0.000085	0.000080	0.00036	0.000085	0.00019	0.00048	0.00024	0.000080	0.00033	0.000050	0.000015
Se (mg/L)	0.021	0.0029	0.036	0.0095	0.014	0.013	0.012	0.020	0.0069	0.0066	0.0024	0.0068

ED_005285_00000283-00308

Sample	232	233	234	235	237	238	239	240	244	245	247	248
Sr (mg/L)	0.29	0.46	0.40	0.74	1.2	3.0	3.1	2.5	1.1	0.45	0.67	0.29
Tl (mg/L)	<0.000024	<0.000024	<0.000024	0.00015	<0.000024	0.00014	0.00050	0.000075	<0.000024	<0.000024	0.00013	0.000060
V (mg/L)	<0.000080	<0.000080	<0.000080	<0.000080	<0.000080	0.00037	0.0024	0.0010	<0.000080	0.00094	0.00096	<0.000080
Zn (mg/L)	0.0052	0.0041	0.0062	0.0053	0.0043	0.0040	0.0038	0.0038	0.0057	0.0013	0.013	0.022
EC (uS/cm)	6,150	5,820	4,970	6,610	6,140	5,630	6,140	6,240	6,090	6,150	5,840	6,040
pH (final) (SU)	7.9	8.0	7.8	8.5	8.1	8.0	7.9	7.9	7.3	8.0	7.3	6.6
pH (lab) (SU)	7.7	7.7	7.6	7.8	7.6	7.7	7.6	7.8	7.6	7.8	6.9	7.4

Sample	251	253	255	260	269	270	270.5	296	298	304
Al (mg/L)	0.20	0.14	0.094	0.043	0.22	0.21	0.32	0.22	0.24	0.11
As (mg/L)	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
B (mg/L)	4.7	1.7	0.44	0.75	2.3	7.5	0.099	<0.0078	<0.0078	<0.0078
Ba (mg/L)	0.027	0.022	0.033	0.0019	0.048	0.039	0.041	0.025	0.029	0.034
Be (mg/L)	0.00069	<0.00061	0.00066	<0.00061	0.00072	<0.00061	0.00063	0.00089	<0.00061	0.00066
Ca (mg/L)	771	671	729	643	762	708	652	659	667	670
Cd (mg/L)	0.00054	0.00021	0.000030	<0.000010	0.000045	0.00037	0.00042	<0.000010	<0.000010	0.0019
Co (mg/L)	0.011	0.0094	0.0099	0.0094	0.0091	0.0078	0.0072	0.0072	0.0068	0.0070
Cr (mg/L)	<0.000090	<0.000090	0.00011	0.00025	0.00021	0.00016	<0.000090	<0.000090	<0.000090	<0.000090
Cu (mg/L)	0.0011	0.0020	0.0014	0.0014	0.0016	0.0018	0.0036	0.00070	0.00051	0.0015
Fe (mg/L)	0.0027	0.0017	0.0016	0.0026	0.0052	0.0048	0.0016	0.0016	0.0048	0.0029
Hg (mg/L)	0.00059	0.00029	<0.000015		0.00050	0.00035	0.000037	<0.000015	0.000018	0.00058
K (mg/L)	1.9	0.89	<0.0016	1.1	3.1	4.3	4.6	1.7	1.6	2.5
Mg (mg/L)	58	15	4.1	2.1	38	64	60	1.2	0.29	29
Mn (mg/L)	1.1	0.099	0.0076	0.12	0.22	0.42	0.36	0.044	0.0068	0.23
Mo (mg/L)	0.0055	0.015	0.0024	0.0033	0.0071	0.019	0.021	0.0027	0.00093	0.0026
Na (mg/L)	5.8	3.0	3.2	0.46	19	48	47	3.0	2.0	4.2
Ni (mg/L)	0.0023	0.00058	0.00026	0.00078	<0.00010	0.0035	0.0035	0.00020	<0.00010	0.0023
P (mg/L)	0.094	0.098	0.12	0.10	0.13	0.016	0.013	0.012	0.012	<0.0099

ED_005285_00000283-00309

Sample	251	253	255	260	269	270	270.5	296	298	304
Pb (mg/L)	0.00010	0.000090	0.00010	0.000095	0.000080	0.00010	0.000095	0.00011	0.00011	0.00023
S (mg/L)	887	526	823	481	845	858	608	517	520	544
Sb (mg/L)	0.00022	0.00026	0.000065	0.000050	0.00016	0.00055	0.00064	0.00023	0.00010	0.00026
Se (mg/L)	0.033	0.016	0.0039	0.0098	0.47	0.29	0.37	0.025	0.0087	0.014
Sr (mg/L)	2.0	0.64	0.55	0.21	0.81	0.38	0.36	0.30	0.32	1.9
Tl (mg/L)	0.000050	<0.000024	<0.000024	0.000055	<0.000024	0.00015	0.00013	0.00025	<0.000024	0.000065
V (mg/L)	<0.000080	0.00031	0.0019	<0.000080	0.0014	0.0066	0.0069	0.00054	0.00029	0.00024
Zn (mg/L)	0.0084	0.011	0.085	0.0042	0.0034	0.0046	0.0016	0.0028	0.0078	0.0077
EC (uS/cm)	5,520	6,090	6,030		7,170	7,830	7,250	5,460	4,770	5,860
pH (final) (SU)	8.2	8.0	6.7		7.4	8.0	7.8	8.0	7.7	7.7
pH (lab) (SU)	7.5	7.5	6.6	7.1	7.4	7.6	7.6	7.5	7.5	7.5

ED_005285_00000283-00310

SPLP - Mined Gypsum

Sample	279	281	283	285	287	287.5	289	291	293	295	301	303
Al (mg/L)	0.12	0.13	0.12	0.16	0.15	0.16	0.089	0.20	0.13	0.14	0.12	0.15
As (mg/L)	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
B (mg/L)	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078
Ba (mg/L)	0.026	0.0078	0.022	0.0070	0.023	0.019	0.030	0.0067	0.024	0.038	0.015	0.0074
Be (mg/L)	<0.00061	0.00083	0.00074	0.00072	0.00066	<0.00061	<0.00061	0.00072	0.00065	<0.00061	0.00066	0.00091
Ca (mg/L)	663	654	646	641	648	655	661	651	662	674	653	656
Cd (mg/L)	0.00010	<0.000010	<0.000010	<0.000010	<0.000010	<0.000010	<0.000010	0.000015	<0.000010	<0.000010	<0.000010	<0.000010
Co (mg/L)	0.0074	0.0059	0.0060	0.0063	0.0065	0.0071	0.0063	0.0056	0.0044	0.0027	0.0069	0.0054
Cr (mg/L)	0.00013	<0.000090	0.00013	0.00014	<0.000090	<0.000090	<0.000090	<0.000090	0.00043	0.00043	<0.000090	0.00014
Cu (mg/L)	0.00084	0.00075	0.00061	0.0012	0.0011	0.00047	0.0012	0.0012	0.00070	0.0059	0.0013	0.0018
Fe (mg/L)	0.0017	0.0020	0.0015	0.0018	0.0019	0.0016	0.0019	0.0024	0.0018	<0.00017	0.0027	0.0077
Hg (mg/L)	0.000022	<0.000015	0.000022	0.000018	<0.000015	0.000018	<0.000015	0.000018	<0.000015	<0.000015	<0.000015	<0.000015
K (mg/L)	2.6	1.8	3.5	1.8	2.7	2.8	2.3	3.3	2.4	3.0	2.5	2.0
Mg (mg/L)	0.90	0.94	2.7	1.3	0.94	0.93	0.40	4.8	1.5	1.4	1.2	0.66
Mn (mg/L)	0.021	0.0081	0.0011	0.0019	0.022	0.020	0.020	0.0033	0.0017	0.0010	0.013	0.035
Mo (mg/L)	0.0088	0.00078	0.0034	0.0061	0.0020	0.0020	0.0015	0.0069	0.00073	0.015	0.00098	0.0048
Na (mg/L)	2.7	3.7	17	9.4	2.0	2.5	6.5	2.8	3.0	4.7	6.2	2.3
Ni (mg/L)	0.00025	<0.00010	0.00035	0.0023	0.0043	0.0029	0.00031	0.00077	<0.00010	<0.00010	0.00018	0.00051
P (mg/L)	0.063	0.054	<0.0099	<0.0099	<0.0099	0.014	<0.0099	0.012	<0.0099	<0.0099	<0.0099	0.016
Pb (mg/L)	0.00012	0.00015	0.00012	0.00012	0.00011	0.00012	0.00013	0.00011	0.00011	<0.000010	0.00014	0.00015
S (mg/L)	534	524	520	512	507	523	527	529	518	525	516	516
Sb (mg/L)	0.00033	0.00037	0.0011	0.00043	0.00042	0.0044	0.0011	0.00084	0.00039	<0.0000	0.00041	0.00040
Se (mg/L)	<0.0024	<0.0024	<0.0024	<0.0024	<0.0024	<0.0024	<0.0024	0.0025	<0.0024	<0.0050	<0.0024	<0.0024
Sr (mg/L)	6.4	10	10	10	8.9	8.6	7.9	11	8.9	6.1	9.9	11
Tl (mg/L)	0.0015	<0.000024	<0.000024	0.00021	0.00012	0.00010	<0.000024	0.000070	<0.000024	<0.000024	0.000070	<0.000024
V (mg/L)	0.00086	0.00061	0.0013	0.00013	0.00024	0.00026	0.00089	0.00045	0.0022	0.00065	0.00027	0.00046
Zn (mg/L)	0.0036	0.0037	0.0050	0.0054	0.0032	0.0036	0.0041	0.0030	0.0039	<0.00061	0.0042	0.014

ED_005285_00000283-00311

Sample	279	281	283	285	287	287.5	289	291	293	295	301	303
EC (uS/cm)	6,080	6,000	6,260	4,880	5,560	6,060	5,990	6,180	5,990	5,870	6,030	5,930
pH (final) (SU)	7.4	7.1	7.8	7.7	7.3	7.5	7.3	7.7	7.3	8.6	7.1	7.4
pH (lab) (SU)	7.2	7.6	7.9	7.6	7.5	7.2	7.7	8.2	7.7	7.6	7.3	7.8

DI

FGD Gypsum

Sample	213	216	223	224	225	226	226.5	227	228	229	230
Br (mg/L)	8.3	<0.22	<0.22	<0.22	<0.22	8.0	8.1	<0.22	<0.22	<0.22	<0.22
Cl (mg/L)	77	7.4	15	11	19	77	63	14	32	6.2	6.9
F (mg/L)	12	8.3	4.6	5.5	6.5	6.0	6.0	2.9	5.4	3.0	5.4
NO_2 (mg/L)	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
NO_3 (mg/L)	16	<0.53	<0.53	<0.53	11	12	11	6.6	<0.53	<0.53	<0.53
PO_4 (mg/L)	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63
SO_4 (mg/L)	1,479	1,281	1,277	1,272	1,275	1,351	1,515	1,286	1,318	1,280	1,283
pH (final) (SU)	9.7	9.7	9.6	9.4	9.3	9.3	7.8	9.2	9.3	9.1	9.0
EC (uS/cm)	6,660	5,100	5,070	4,970	5,150	5,620	5,540	5,050	5,300	4,070	5,100

Sample	231	232	233	234	235	237	238	239	240	244	245	247	248
Br (mg/L)	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
Cl (mg/L)	21	9.9	8.7	8.3	28	5.9	10	7.2	10	7.9	7.7	7.3	7.3
F (mg/L)	4.4	4.9	4.8	4.9	6.6	4.6	5.1	3.4	4.8	3.8	3.4	2.7	4.7
NO_2 (mg/L)	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
NO_3 (mg/L)	6.8	<0.53	<0.53	<0.53	8.0	<0.53	<0.53	<0.53	<0.53	<0.53	<0.53	<0.53	<0.53
PO_4 (mg/L)	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63
SO_4 (mg/L)	1,277	1,285	437	1,305	1,159	1,303	1,296	1,297	1,308	1,300	1,246	1,303	1,307
pH (final) (SU)	8.8	8.0	8.4	8.3	8.4	8.3	8.1	8.0	8.2	8.5	8.6	7.7	8.4
EC (uS/cm)	6,340	5,150	4,940	5,990	5,340	4,970	4,990	4,990	3,530	5,940	4,930	4,930	6,240

ED_005285_00000283-00312

Sample	251	253	255	269	270	270.5	296	298	304
Br (mg/L)	7.7	<0.22	<0.22	9.0	<0.22	8.0	<0.22	<0.22	8.0
Cl (mg/L)	45	18	8.1	41	75	61	7.6	6.3	65
F (mg/L)	9.6	7.4	2.9	14	13	11	4.5	5.9	7.1
NO_2 (mg/L)	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
NO_3 (mg/L)	8.3	6.7	<0.53	9.6	11	9.9	<0.53	<0.53	7.4
PO_4 (mg/L)	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63
SO_4 (mg/L)	1,411	1,359	1,206	1,444	1,549	1,592	1,372	1,347	1,431
pH (final) (SU)	9.2	8.5	7.8	8.0	8.3	8.1	8.4	8.4	8.6
EC (uS/cm)	5,200	5,220	5,030	5,780	7,380	6,290	4,980	5,020	5,540

Mined Gypsum

Sample	279	281	283	285	287	287.5	289	291	293	295	301	303
Br (mg/L)	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
Cl (mg/L)	6.3	7.4	22	7.7	6.1	6.5	9.3	9.5	6.6	10	11	6.3
F (mg/L)	2.7	2.6	2.7	2.7	2.6	2.6	2.7	2.8	2.6	2.7	2.6	2.6
NO_2 (mg/L)	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
NO_3 (mg/L)	7.5	<0.53	12	9.3	8.9	8.5	7.4	13	8.1	<0.53	8.5	<0.53
PO_4 (mg/L)	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63	<0.63
SO_4 (mg/L)	1,350	1,339	1,358	1,353	1,389	1,411	1,461	1,414	1,409	1,414	1,379	1,400
pH (final) (SU)	8.3	7.6	8.7	8.6	8.1	8.5	8.8	8.8	8.3	9.0	8.1	8.1
EC (uS/cm)	4,990	5,060	5,300	5,030	4,980	5,000	5,100	5,150	5,220	5,090	5,060	5,010

ED_005285_00000283-00313

Gypsum Purity

FGD Gypsum	
Sample	%$CaSO_4$
213	95
216	98
223	98
224	98
225	96
226	97
227	96
228	97
229	94
230	96
231	98
232	98
233	98
234	98
235	90
237	96
238	96
239	93
240	97
244	97
245	99
247	99
248	98
251	94
253	95
255	99
260	98
269	94
270	92
296	93
298	97
304	93

Mined Gypsum	
Sample	%$CaSO_4$
279	88
281	98
283	75
285	72
287	95
289	72
291	66
293	90
295	84
301	89
303	91

ED_005285_00000283-00314

C
STATISTICAL CALCULATIONS

Two-Group Statistical Comparison Method

Data distributions for many constituents in mined and FGD gypsum total composition and leachate sample groups were non-parametric. Therefore, a non-parametric two-group comparison test was used. If the assumptions of the statistical two-group comparison test were not achieved, then a graphical comparison approach was used.

Wilcoxon Rank-Sum Test

The Wilcoxon rank-sum test, also known as the Mann-Whitney U test, was used for statistical comparison of datasets. The null hypothesis of this test is that the two datasets come from the same population. The alternative hypothesis is that the datasets come from different populations, with one having a higher median concentration.

This test assumes that the two datasets have equal variances, but makes no assumption concerning the normality of the dataset (USEPA, 2009). Variance was tested using Levene's test. Both tests are documented in USEPA (2009).

The Wilcoxon test was tested at 90%, 95%, and 99% confidence. The 90% confidence level is more appropriate in this case based on testing with one of the more extreme comparisons, bromide in the SPLP leaching data. The median bromide concentrations were equal at the detection limit; however, the range of values for FGD gypsum was influenced by the unwashed samples. Based on this difference, the statistical calculation should show FGD gypsum as having higher bromide concentration. At 95% and 99% confidence, the null hypothesis was accepted for the Wilcoxon test (the datasets are from the same population), and the alternative hypothesis (datasets from different populations—meaning FGD gypsum leachate concentrations higher than mined gypsum) was accepted at 90% confidence. Testing this method on the SPLP data indicated that the only other leachate constituent that differed at 90% confidence was aluminum, where the null hypothesis was also accepted at 99% confidence, and the alternative (FGD higher) was accepted at 90%. These results indicate that the null hypothesis is less likely to be accepted at 90% confidence than at 99% confidence.

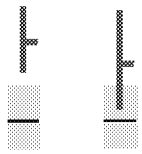
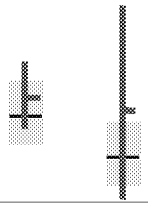
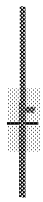
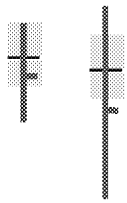
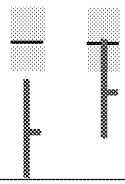
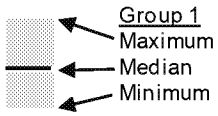
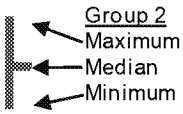
Levene's test was performed at 99% confidence. For both tests, the MDL was substituted for non-detects in order to be consistent with the approach used in the graphical comparisons.

Graphical Comparison Method

If Levene's test indicated that the variances were not equal, then a graphical comparison was used. The graphical comparison criteria are listed in Table C-1.

ED_005285_00000283-00316

Table C-1
Graphical Two-Group Comparison Criteria

	Above range if the lowest Group 2 concentration is greater than the highest Group 1 concentration *or* the range is overlapping higher and the Group 2 median is greater than the highest Group 1 concentration.
	Overlapping higher if the highest Group 2 concentration is higher than the highest Group 1 concentration, *or* if the Group 2 range is overlapping and the median Group 2 concentration is greater than the highest Group 1 concentration.
	Overlapping if the highest Group 2 concentration is greater than the highest Group 1 concentration *and* the lowest Group 2 concentration is lower than the lowest Group 1 concentration (unless the Group 2 median falls outside this range, see overlapping higher and overlapping lower).
	Within if the highest Group 2 concentration is less than the highest Group 1 concentration *and* the lowest Group 2 concentration is higher than the lowest Group 1 concentration.
	Overlapping lower if the highest Group 2 concentration is less than the highest Group 1 concentration, *or* if the Group 2 range is overlapping and the median Group 2 concentration is less than the lowest Group 1 concentration.
	Below range if the highest Group 2 concentration is less than the lowest Group 1 concentration *or* the range is overlapping lower and the Group 2 median is less than the lowest Group 1 concentration.
Where:	  Group 1 is represented by the thick gray bar and Group 2 is represented by the green line.

ED_005285_00000283-00317

Outlier Calculation

Potential outliers were visually checked by sorting the results and reviewing the maximum and minimum values, and statistically evaluated using the box plot method described in USEPA (2009). The box plot method determines outliers as values greater than:

$$\tilde{X}_{0.75} + K * (\tilde{X}_{0.75} - \tilde{X}_{0.25})$$

Or values less than:

$$\tilde{X}_{0.25} - K * (\tilde{X}_{0.75} - \tilde{X}_{0.25})$$

Where:

K = 1.5 to identify mild outliers or 3.0 to identify extreme outliers

$\tilde{X}_{0.25}$ = the 25th percentile

$\tilde{X}_{0.75}$ = the 75th percentile

Since the data used in this analysis were largely derived from samples collected by the same contractor, and there was no inter-laboratory variability, only extreme outliers were calculated.

Potential outliers were calculated for both straight and log-transformed datasets. Skewness was then calculated to determine the normality of each dataset, and the outliers were identified based on the dataset (straight or log-transformed) that most closely approximated the normal distribution.

Review of Total Composition Outlier Results

FGD Gypsum

One thallium result (sample 238) was excluded from further analysis because it was a non-detect at a detection level higher than the highest detected value.

Two FGD gypsum total composition results were determined to be extreme statistical outliers according to the box plot screening method of USEPA (2009):

- Arsenic in sample 226. The concentration in this sample (11.1 mg/kg) was only slightly higher than the next highest concentration (10.0 mg/kg), and there was no detail about the sample collection or plant configuration to make this sample stand out from the others. A blind replicate analysis performed on this sample yielded an arsenic concentration of 12.6 mg/kg. Based on these observations, this concentration is a reflection of variability in the arsenic results rather than an outlier.
- Lead in sample 239. The concentration in this sample (8.3 mg/kg) was a factor of 4 greater than the next highest concentration (2.0 mg/kg). However, there was no detail about the sample collection or plant configuration to make this sample stand out from the others. Therefore, this concentration is a reflection of variability in the lead results rather than an outlier.

Mined Gypsum

Two beryllium results (samples 289 and 291) were excluded from further analysis because they were non-detects at a detection level higher than the highest detected value. No mined gypsum total composition results were identified as extreme outliers using the method of USEPA (2009).

Review of SPLP and DI Extract Outlier Results

FGD Gypsum

There were several potential outliers identified using the box plot screening method of USEPA (2009):

- Br in samples 213, 226, 251, 269, and 304. Bromide concentrations in these samples ranged from 7.7 to 9.0 mg/L. All other bromide concentrations were lower than the detection limit of 0.22 mg/L. These samples were either unwashed or "washed by sluicing" (226) and it is likely that the bromide is a residual that would otherwise be removed during the washing process. These samples also had relatively high Cl (41-77 mg/L) and NO_3 (7.4 to 16 mg/L).[3] Since these concentrations appear to represent unwashed FGD gypsum rather than an anomalous sample or laboratory procedure, they were included in the analysis.
- Fe in samples 227 (0.016 mg/L) and 248 (0.040 mg/L). There was nothing unusual about the pH, concentration of other constituents, or sample and plant attributes for these samples, and they were included in the analysis.
- K in sample 213 (7.2 mg/L). This sample also had the highest B, Cl, Mn, Na, and NO_3 concentrations in the SPLP dataset—although none of these were statistical outlier values. The sample is unwashed, but otherwise was not unusual in terms of sample collection or plant attributes. Its pH was the most alkaline of the SPLP and DI samples (10.07 and 9.73, respectively). Given the above observations, this result is considered an example of sample variability rather than an outlier and was included in the analysis.
- Be in samples 251, 233, 269, and 296. These concentrations ranged from 0.00069 to 0.00089 mg/L, were less than a factor of two higher than the next highest concentration, and do not appear to be true outliers.
- Pb in sample 248 (0.0013 mg/L). Like the Fe concentration in this sample, it does not appear to represent a true data outlier.
- Zn in sample 255 (0.085 mg/L). This was a post-processed sample, where fly ash entrained with the gypsum was removed. However, this sample was not unusual in terms of other elements, including coal ash indicator constituents, or pH, so the zinc value was included in the analysis.

[3] There were two unwashed gypsum samples that had non-detectable Br concentrations (270 and 235), both of which also had relatively high Cl and NO_3 concentrations.

ED_005285_00000283-00319

Mined Gypsum

There were several potential outliers identified using the box plot screening method of USEPA (2009):

- Fe, Co, Pb, and Zn in samples 295. Sample 295 had four calculated outlier results on the low end of the concentration range. No other sample had an outlier on the low end of the concentration range. The solubility for all of these constituents is pH dependent, and this sample had the highest pH of the group (8.6 SU, compared to all other samples with pH between 7 and 8 SU). Sample 295 also had the highest pH of the DI extracts, indicating that the pH result is not anomalous; therefore, these results were not excluded from the analysis, because they appear to be related to the pH of this sample.
- Fe and Zn in sample 303. This sample has a typical pH for the mined gypsum SPLP samples, and neither of these constituents had high concentration in the total composition analysis for this sample—in fact both were at the low end of their respective total composition ranges. Iron and zinc do not interfere with each other in ICP-MS analysis. These analytical results may be anomalous; however, concentrations are low (lower than 0.015 mg/L), so they were flagged for careful review but included in the analysis.
- P in samples 279 and 281. These were two of only four P detects, and the outlier designation is mathematical rather than the result of an anomaly; therefore, these results were included in the analysis.
- Cd in samples 279 and 291. These were the only two Cd detects, and the outlier designation is mathematical rather than the result of an anomaly; therefore, these results were included in the analysis.
- Cu in sample 295. This sample had the highest pH of the batch. The solid composition was not relatively high, and it is possible that this result is an outlier. However, the concentration is less than a factor of 5 higher than the next highest value, and is low (0.006 mg/L); therefore, it was flagged for careful review, but included in the analysis.
- Se in samples 291 and 295. The selenium concentration in sample 295 is a non-detect at a detection limit higher than the only detect, which was from sample 291. The Se result from sample 295 was excluded from the analysis due to its high detection limit. The detect from sample 291 was slightly higher than the detection limit, indicating that the outlier designation was mathematical rather than indication of an anomalous result; therefore this result was included in the analysis.

Review of TCLP Extract Outlier Results

FGD Gypsum

The box plot screening method (USEPA, 2009) flagged all detects for As (1 outlier), Cd (6), and Se (7) as outliers. These flags are mathematical rather than anomalous samples and all were included in the analysis. One Hg result was also flagged as an outlier (sample 269, 0.00058 mg/L). This result was a factor of 5 higher than the next highest Hg result and an order of magnitude higher than most of the other Hg TCLP values. However, this concentration occurred at the high end of the pH range (6.3 SU) where one of the two next highest

concentrations occurred, and may be valid due to the relatively high pH of this sample (see (Figure C-1). Because of this uncertainty, this sample was not excluded from the analysis.

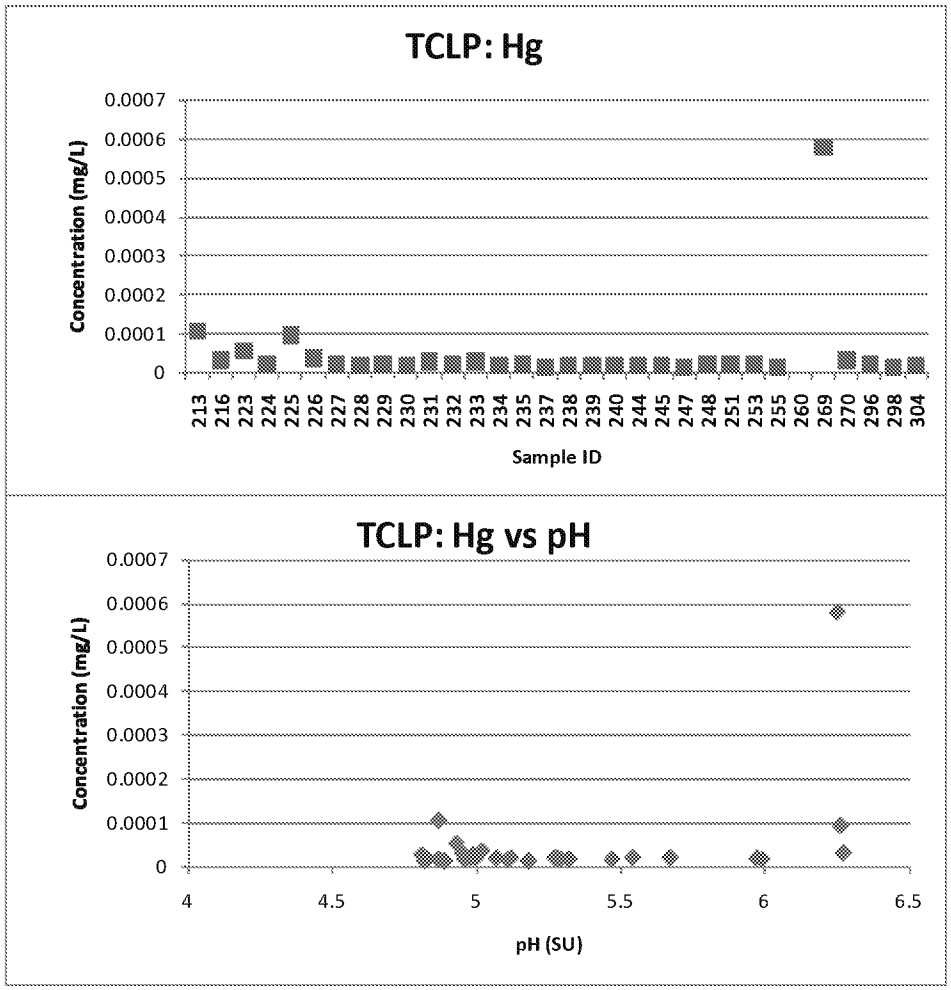


Figure C-1
Hg concentrations in FGD gypsum TCLP extracts (top), compared to final pH in the extract (bottom)

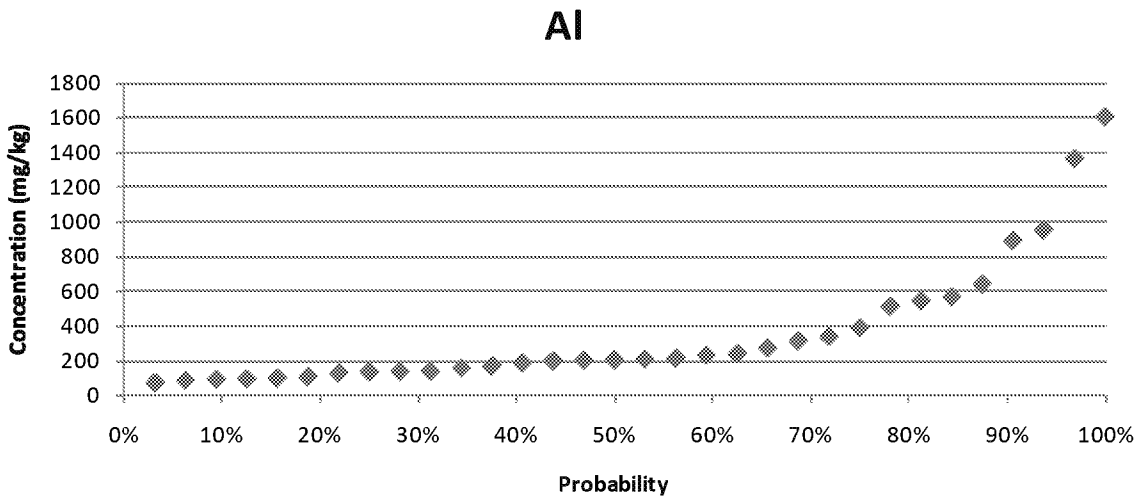
Mined Gypsum

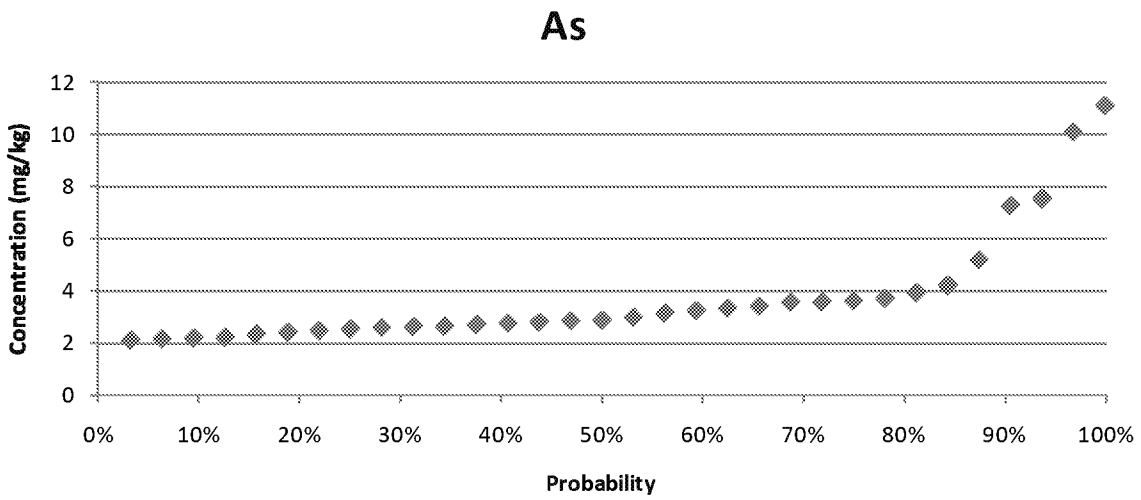
There were no extreme outlier results identified in the mined gypsum TCLP results.

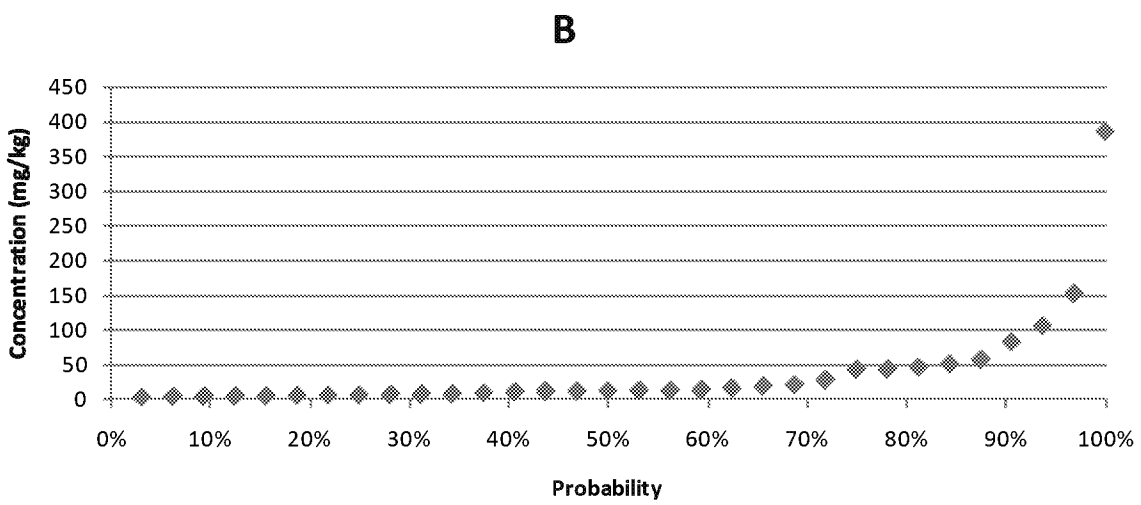
D
PROBABILITY PLOTS

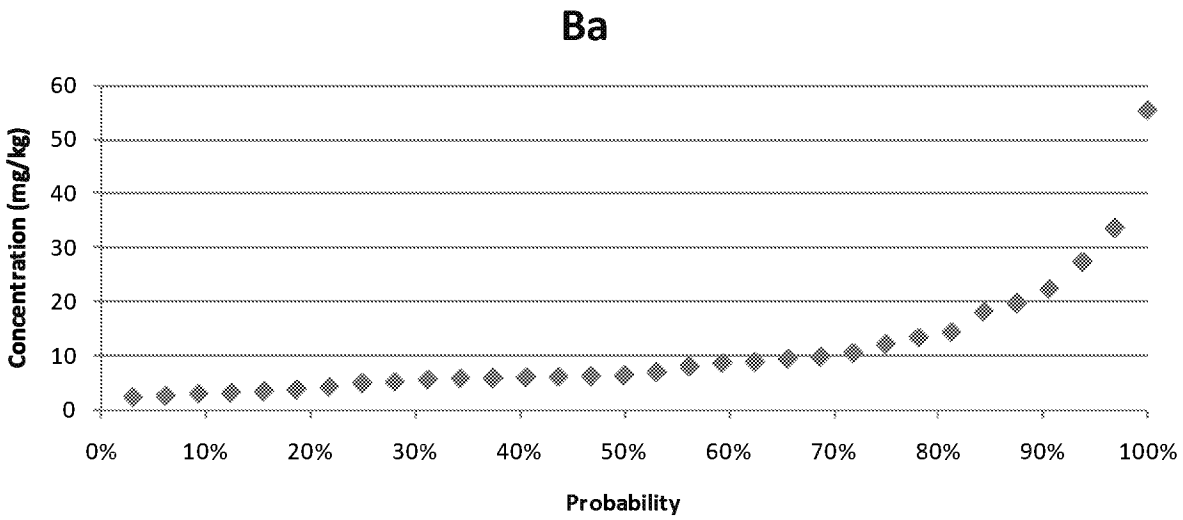
ED_005285_00000283-00322

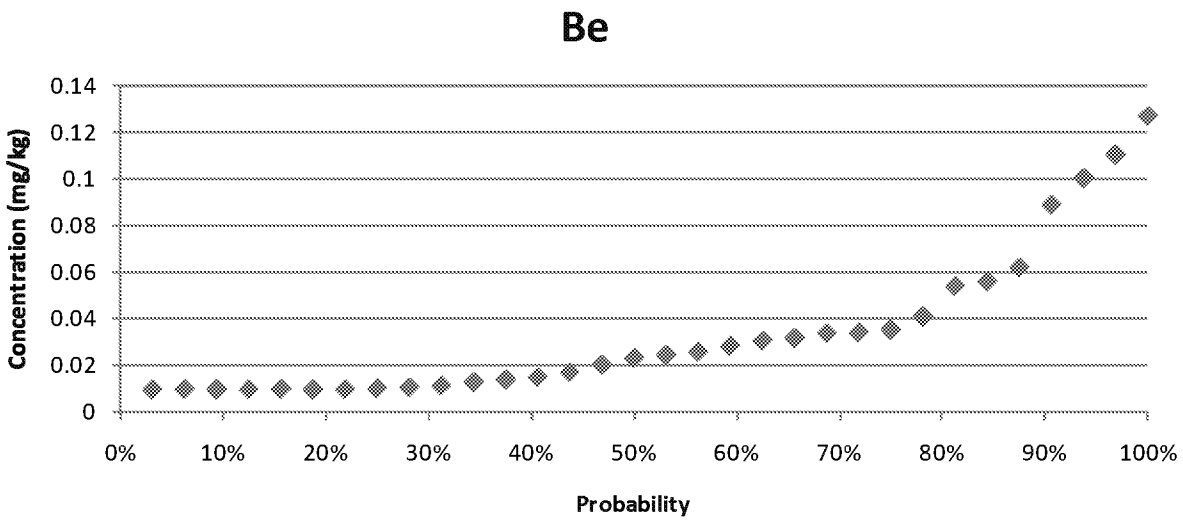
Total Composition

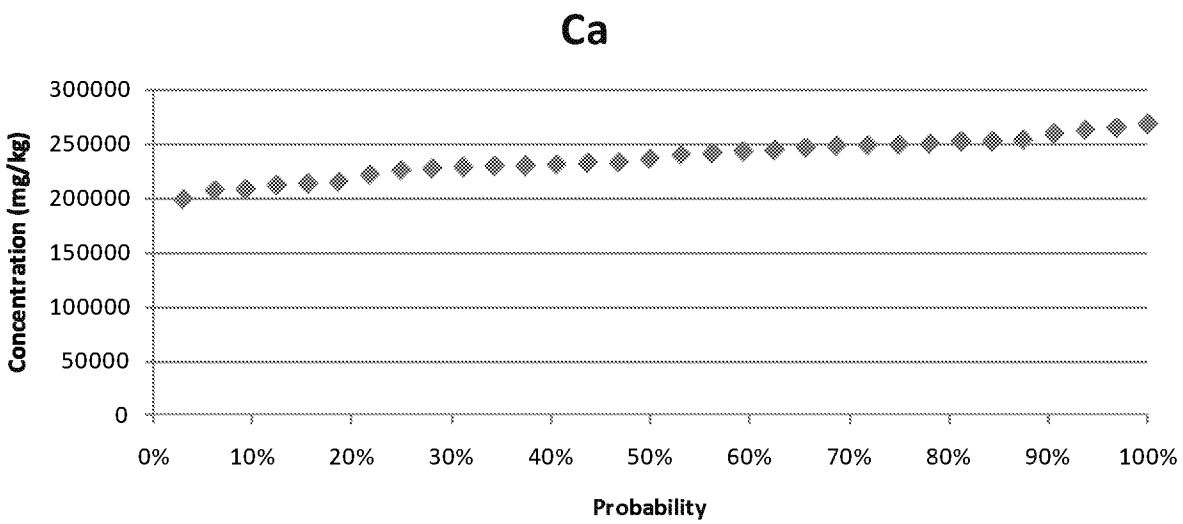


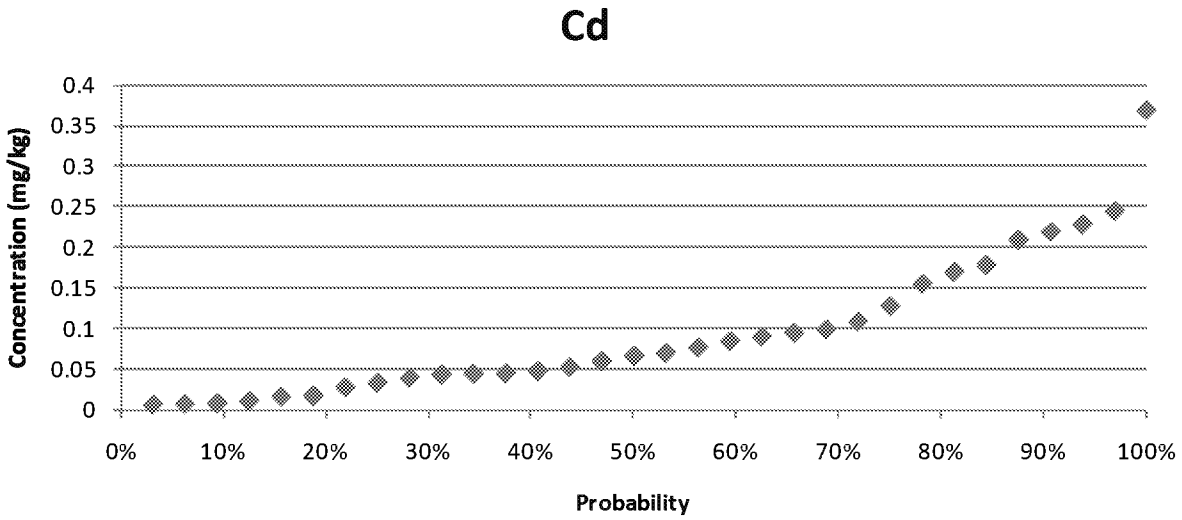


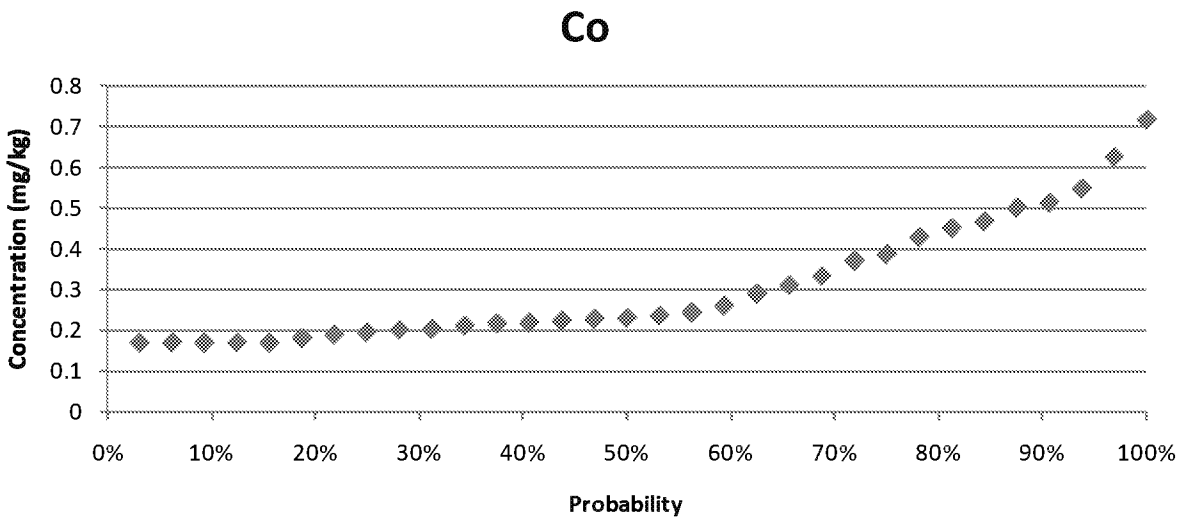


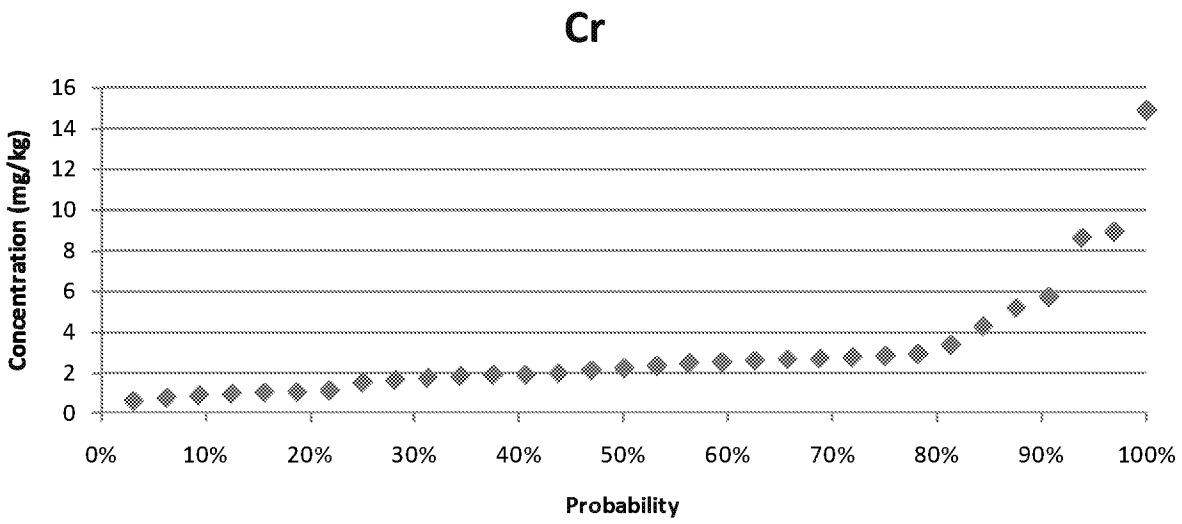

Ba
Concentration (mg/kg)
60
50
40
30
20
10
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

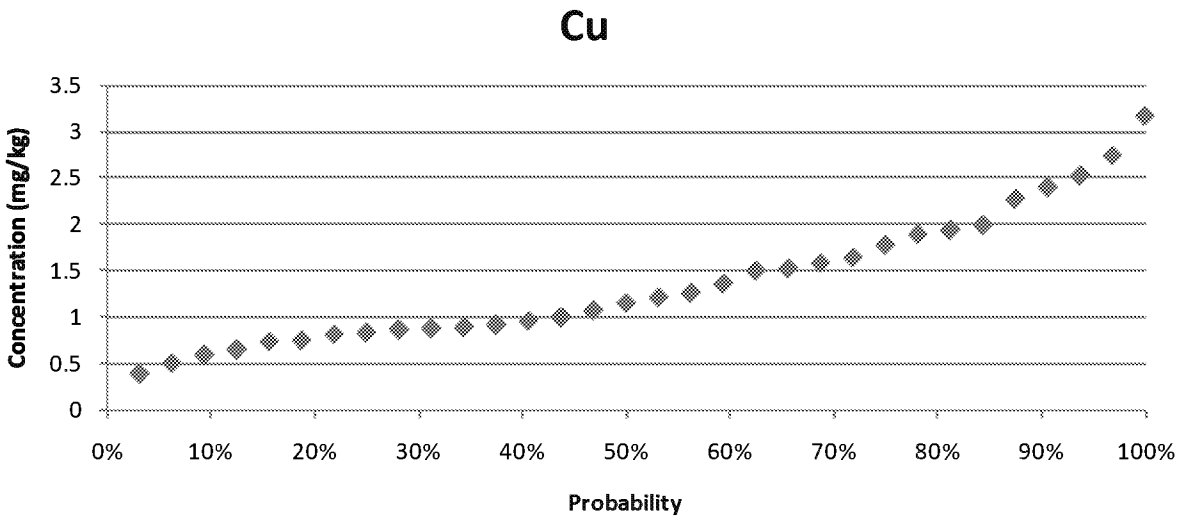

Be
Concentration (mg/kg)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

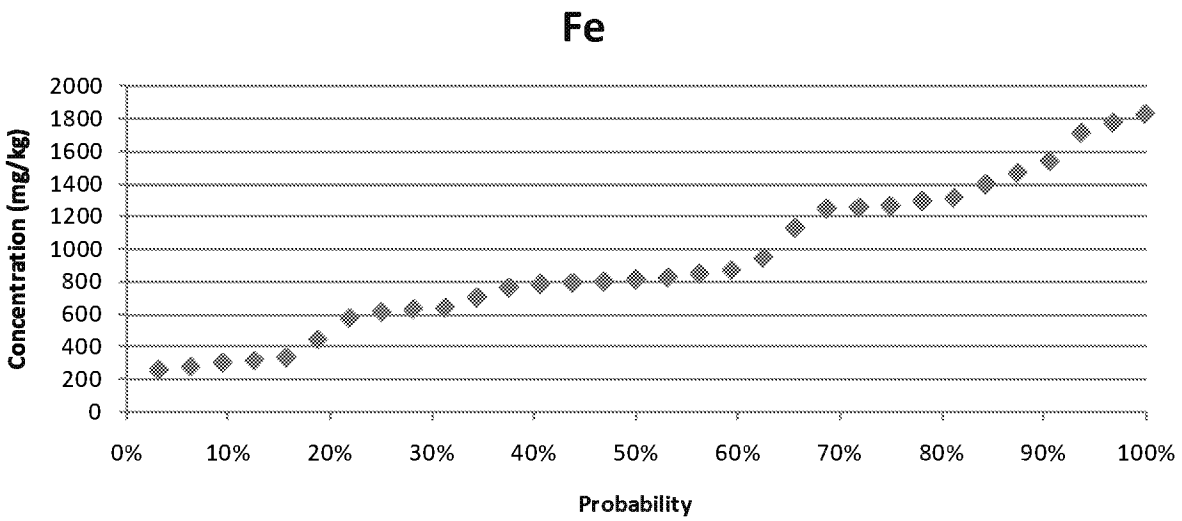

Ca
Concentration (mg/kg)
300000
250000
200000
150000
100000
50000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

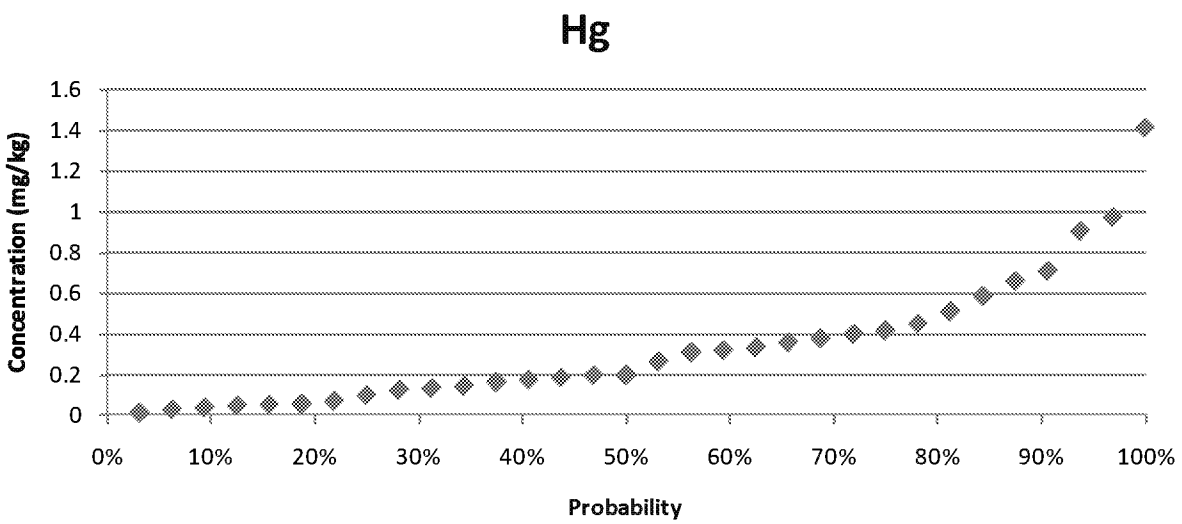

Cd
Concentration (mg/kg)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

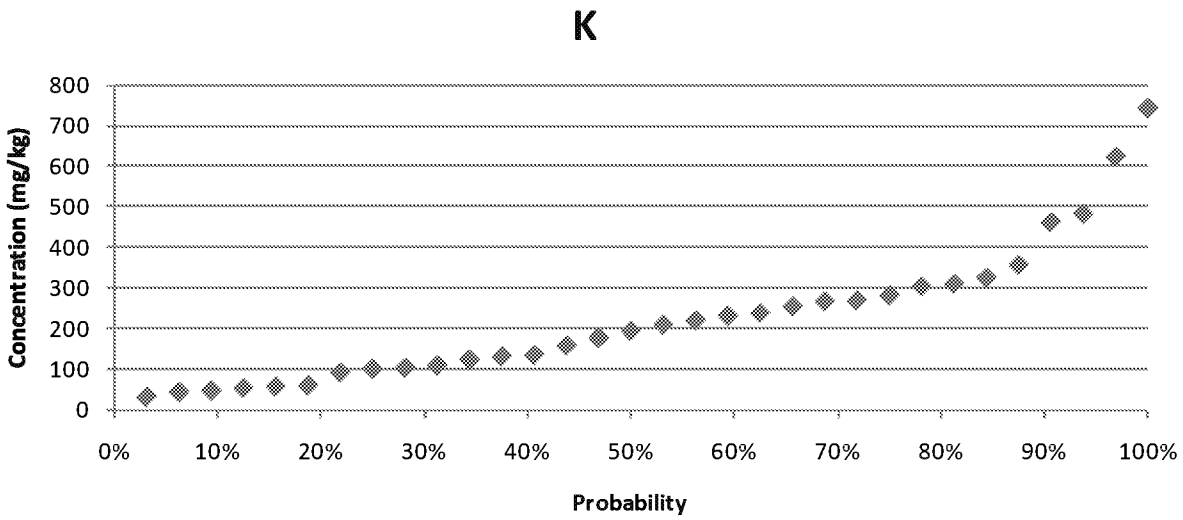

Co
Concentration (mg/kg)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

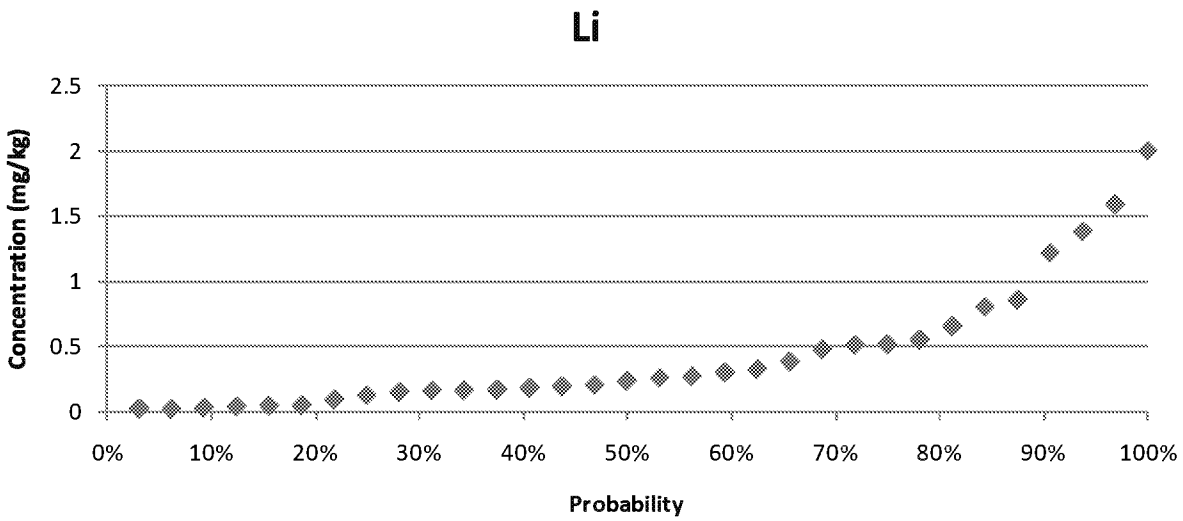

Cr
Concentration (mg/kg)
16
14
12
10
8
6
4
2
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

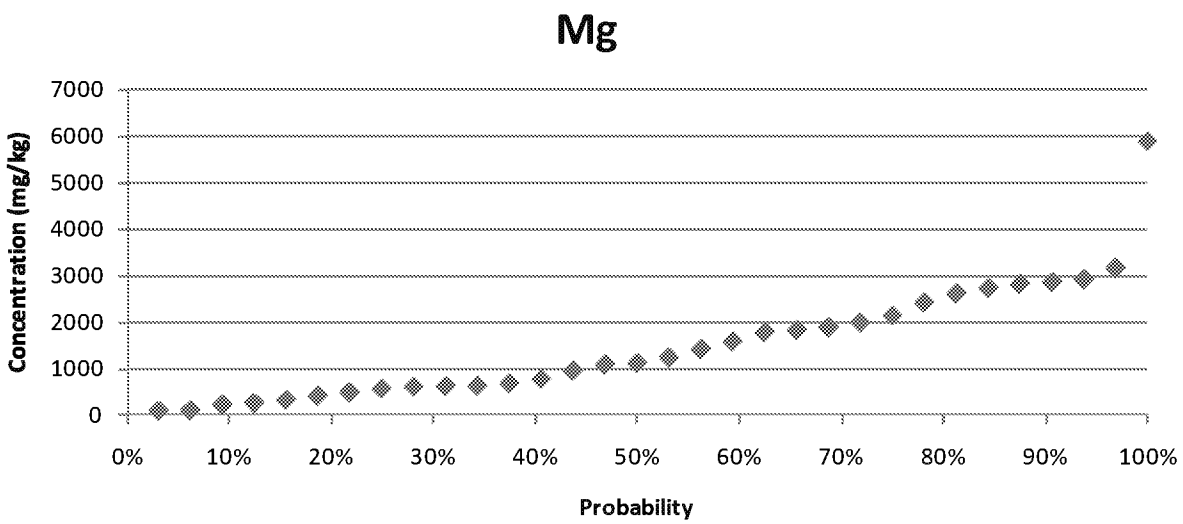

Cu
Concentration (mg/kg)
3.5
3
2.5
2
1.5
1
0.5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

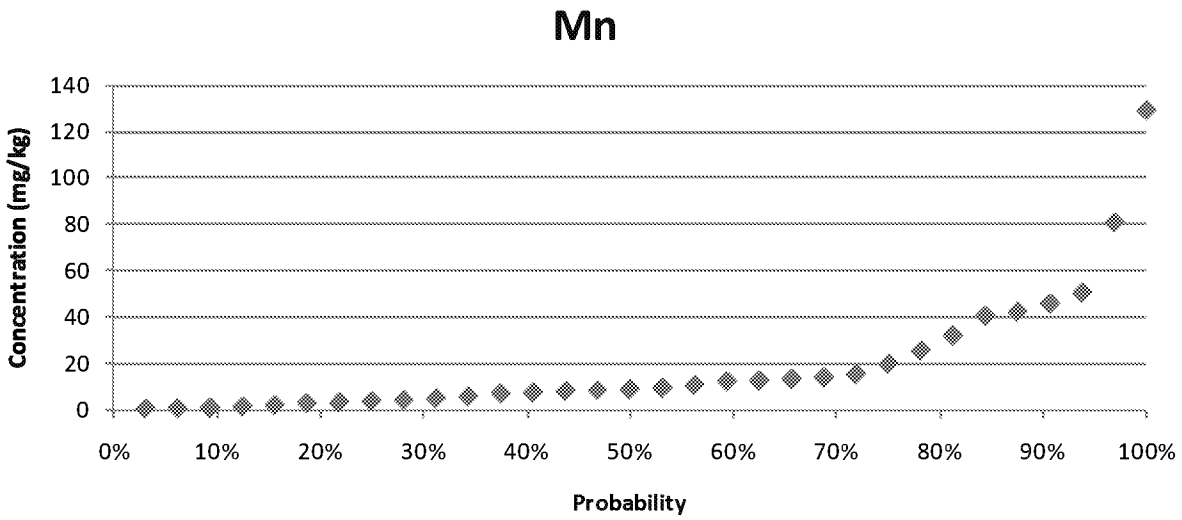

Fe
Concentration (mg/kg)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

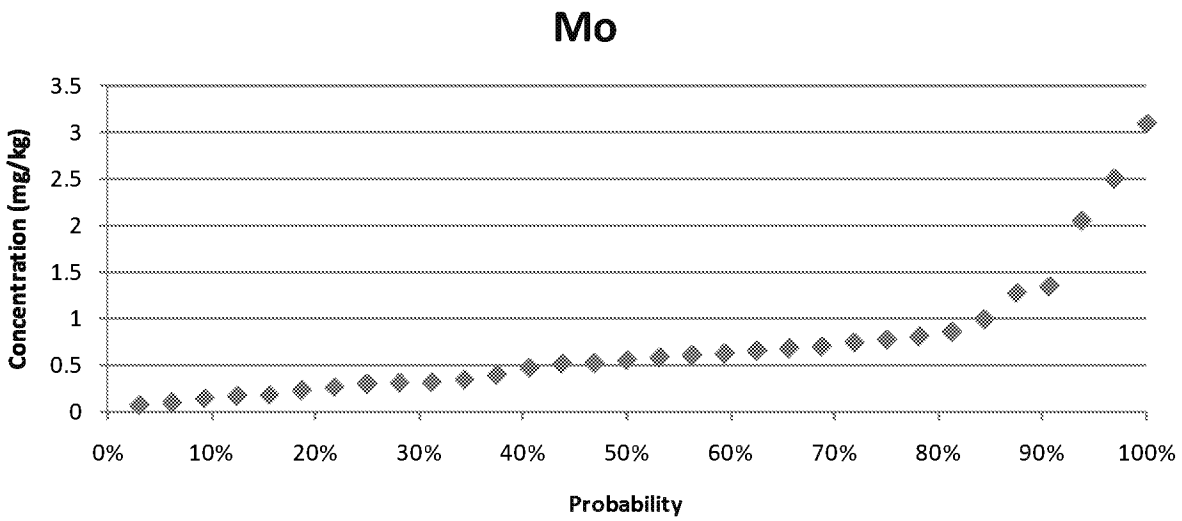

Hg
Concentration (mg/kg)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

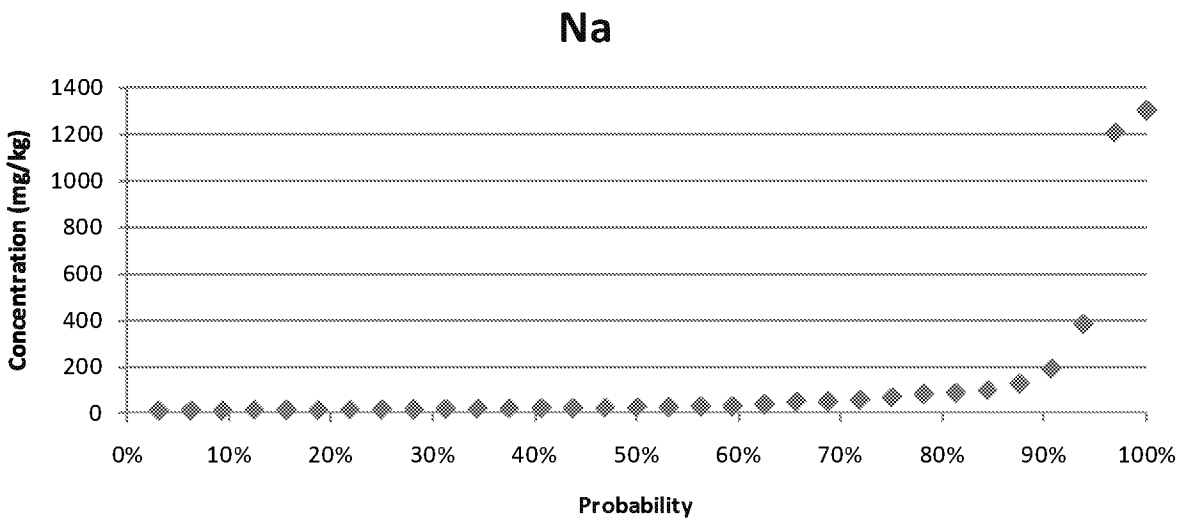

K
Concentration (mg/kg)
800
700
600
500
400
300
200
100
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

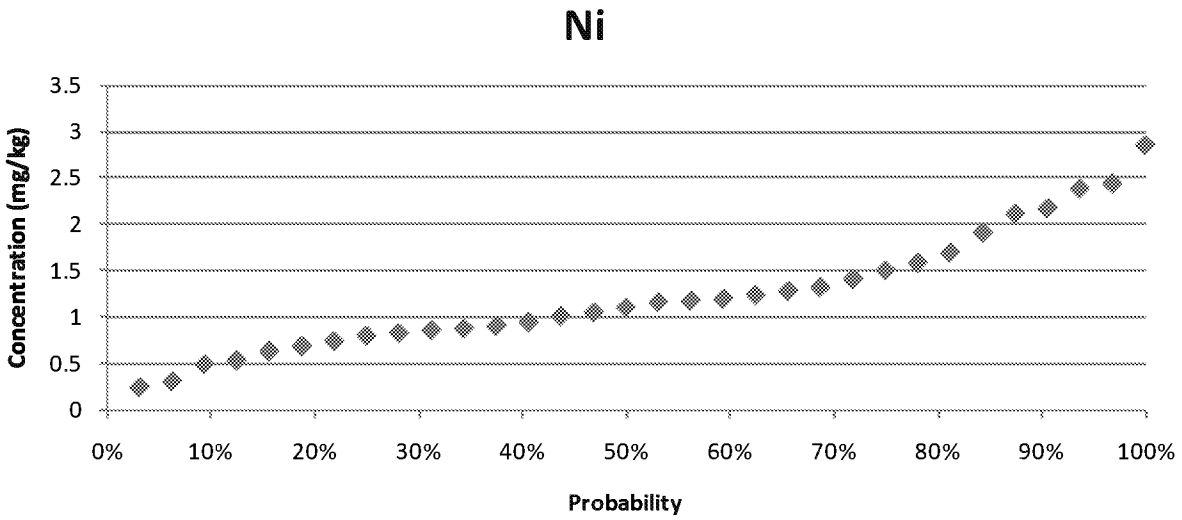

Li
Concentration (mg/kg)
2.5
2
1.5
1
0.5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

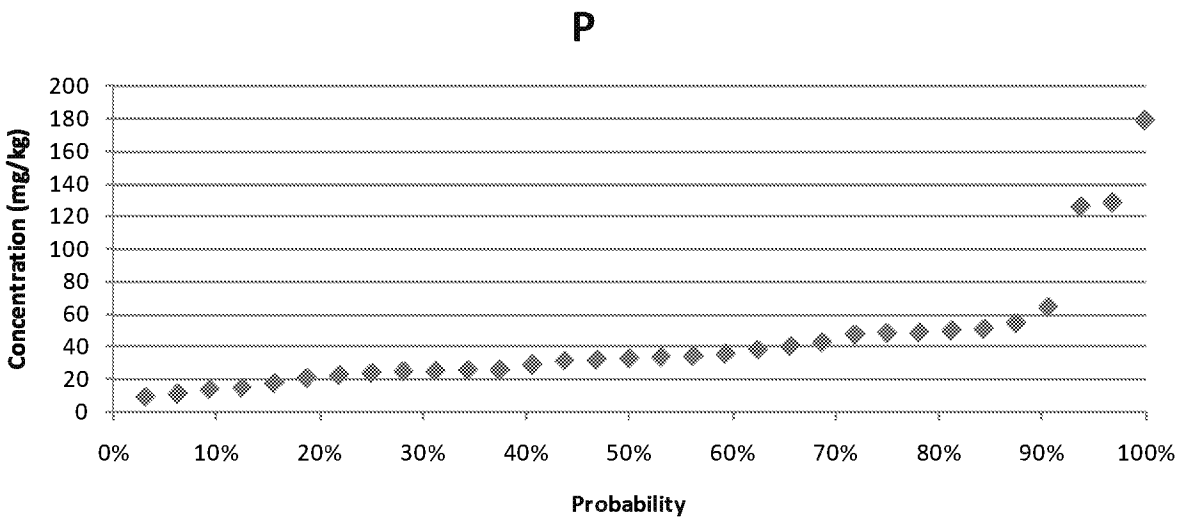

Mg
Concentration (mg/kg)
7000
6000
5000
4000
3000
2000
1000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

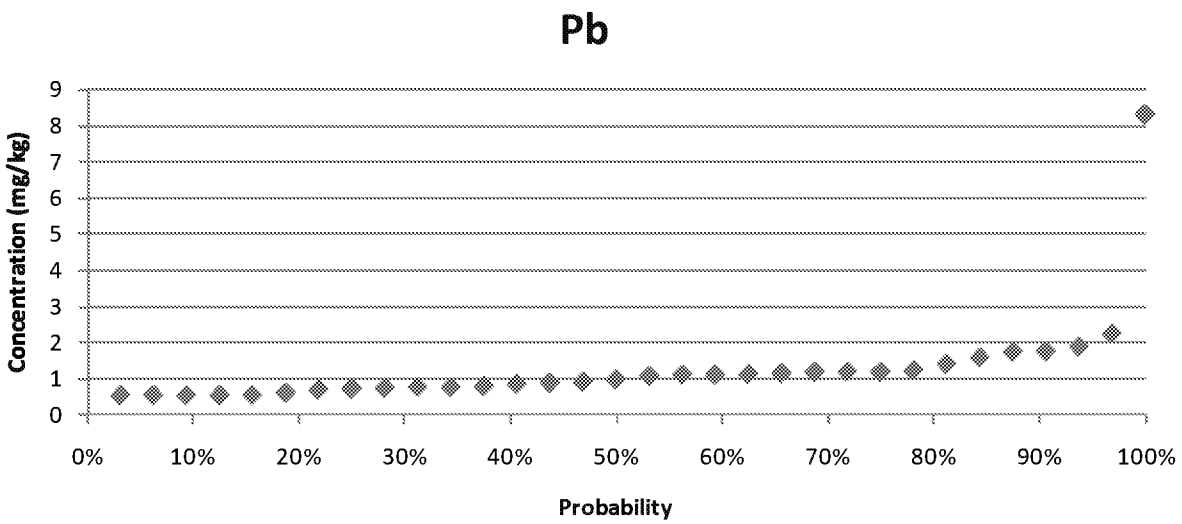

Mn
Concentration (mg/kg)
140
120
100
80
60
40
20
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

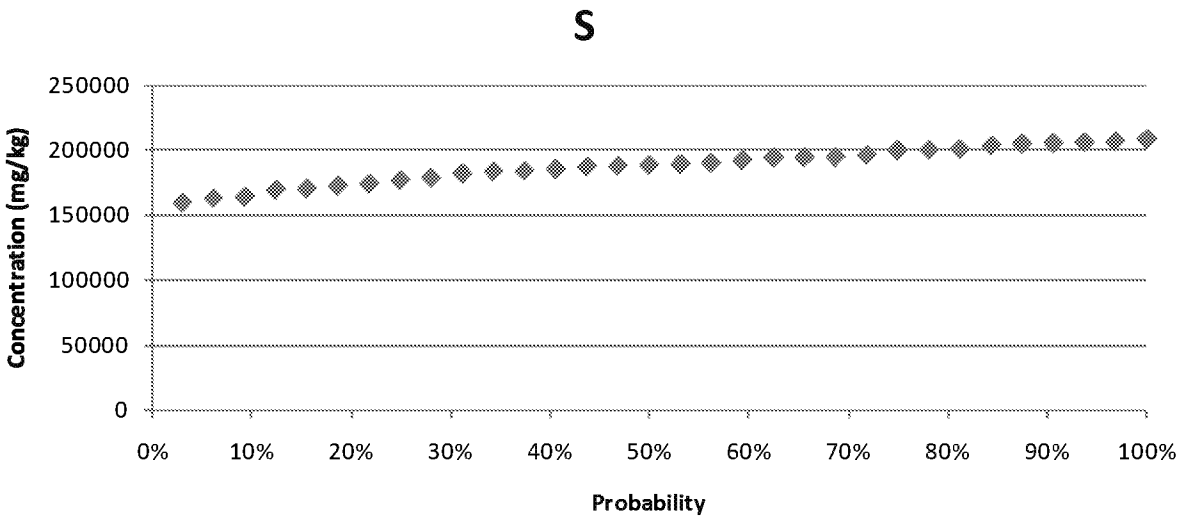

Mo
Concentration (mg/kg)
3.5
3
2.5
2
1.5
1
0.5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

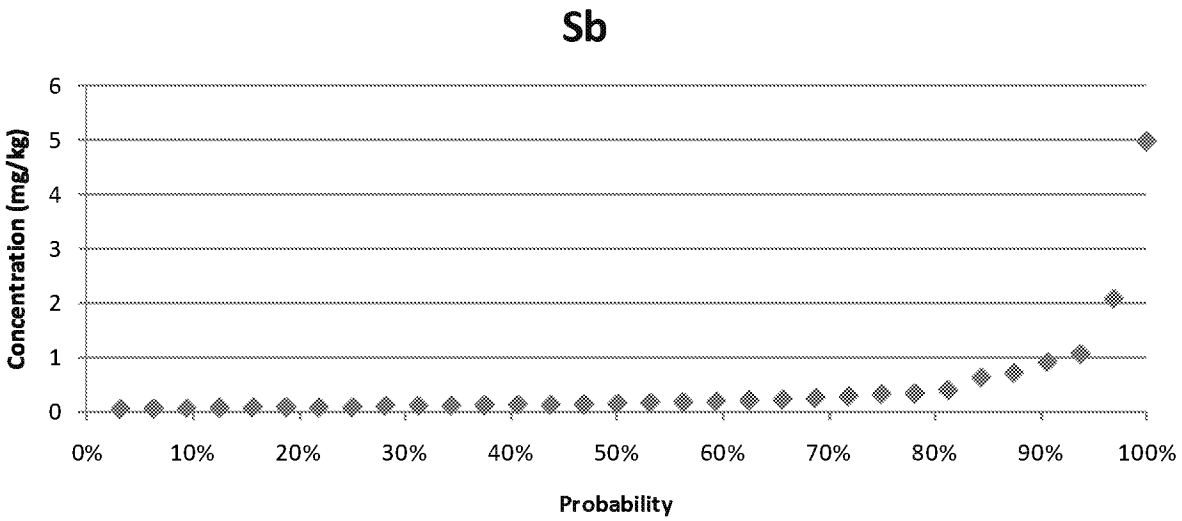

Na
Concentration (mg/kg)
1400
1200
1000
800
600
400
200
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

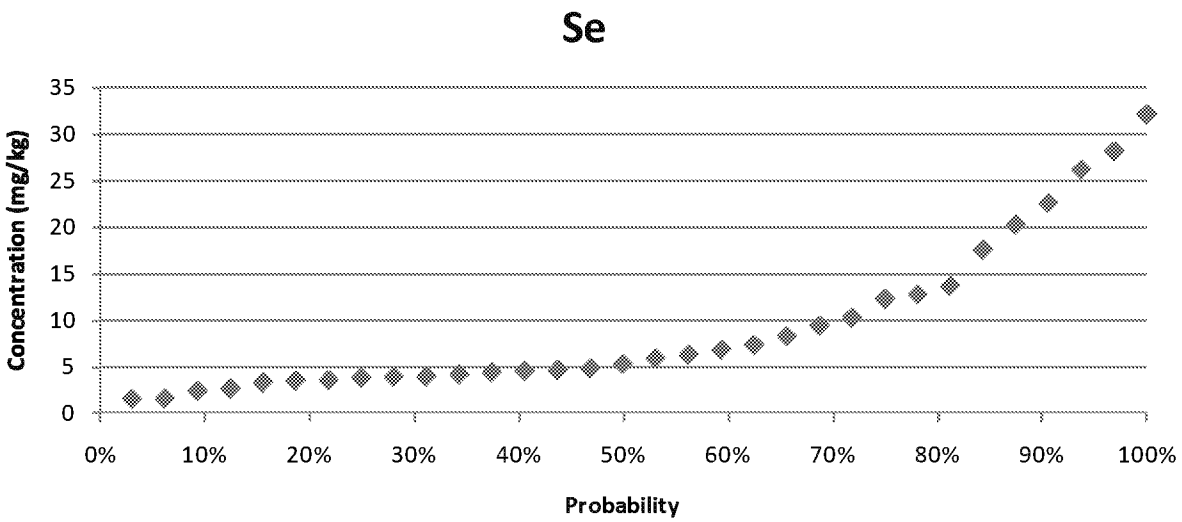

Ni
Concentration (mg/kg)
3.5
3
2.5
2
1.5
1
0.5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

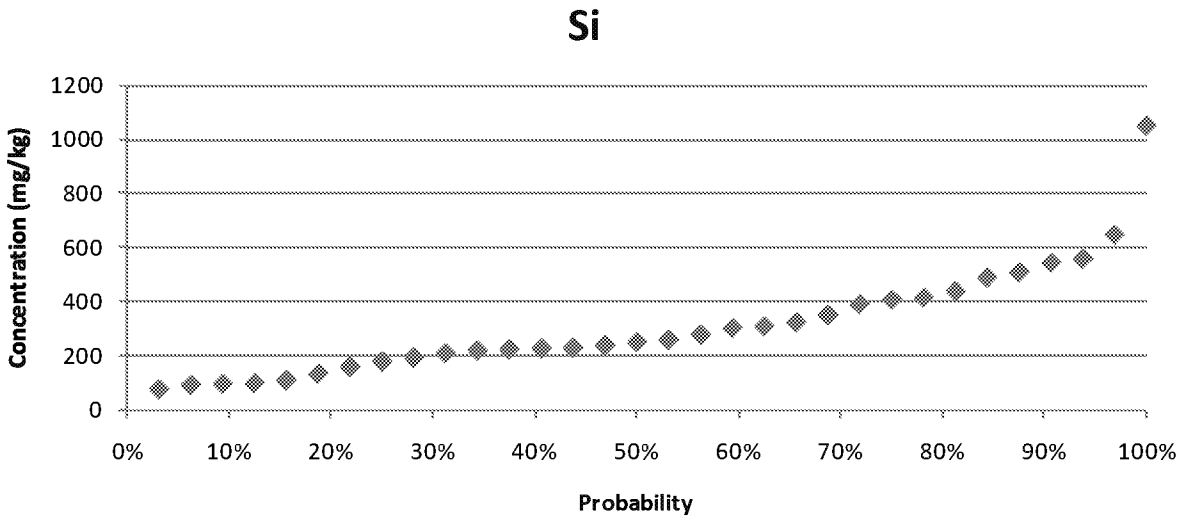

P
Concentration (mg/kg)
200
180
160
140
120
100
80
60
40
20
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

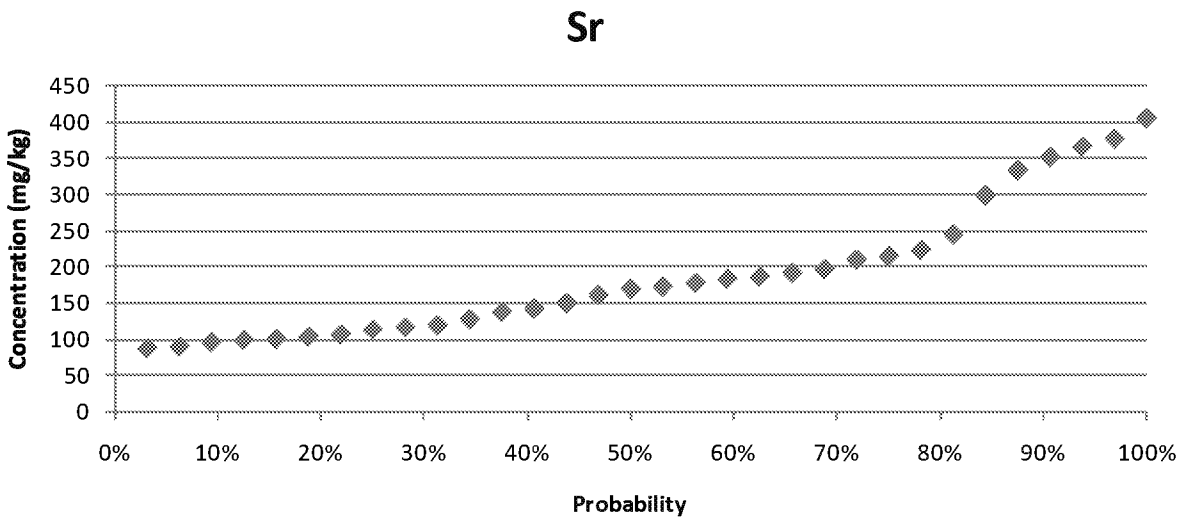

Pb
Concentration (mg/kg)
9
8
7
6
5
4
3
2
1
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

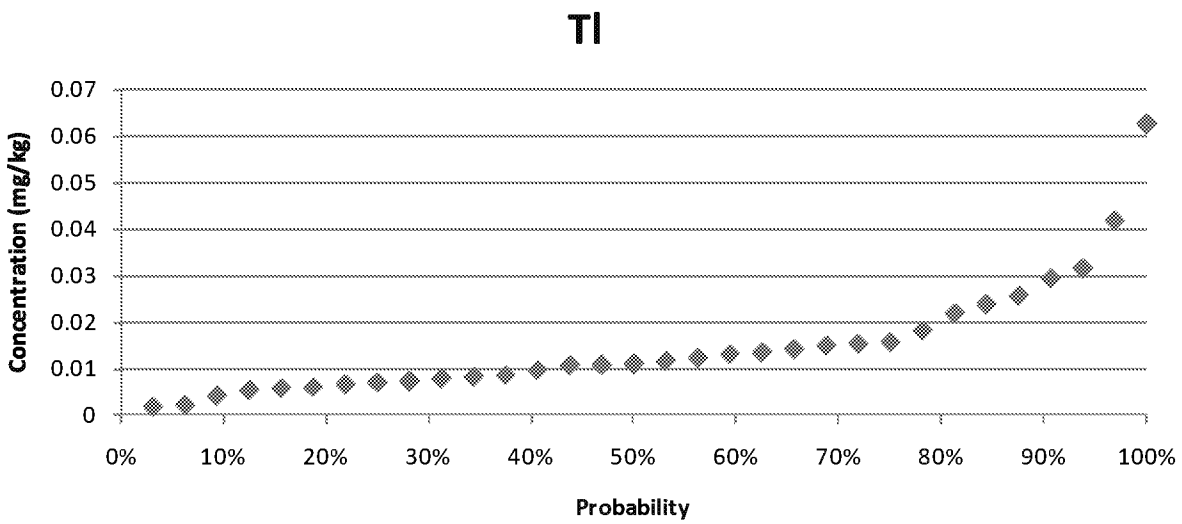

S
Concentration (mg/kg)
250000
200000
150000
100000
50000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

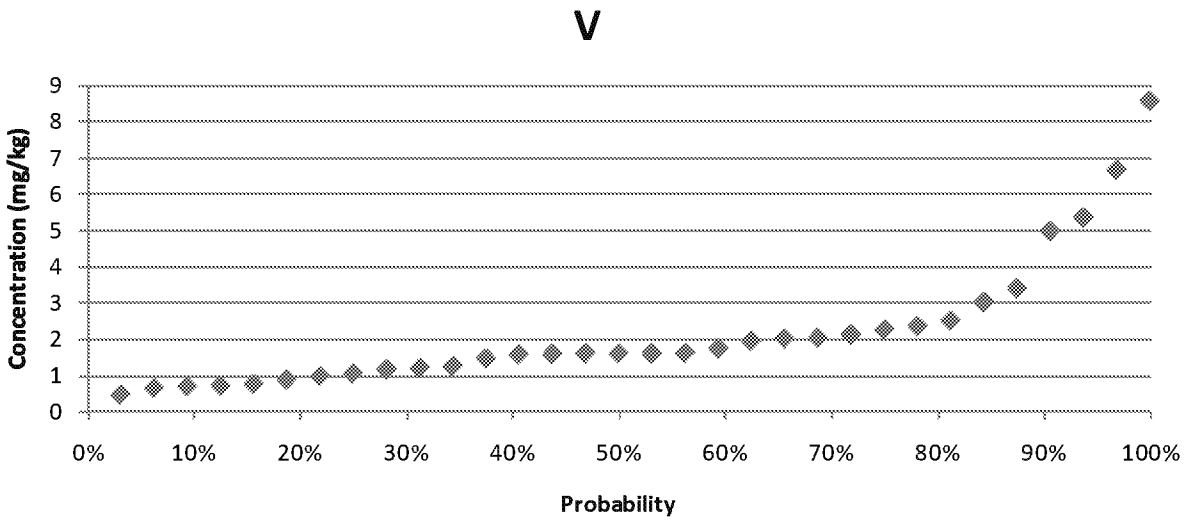

Sb
Concentration (mg/kg)
6
5
4
3
2
1
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

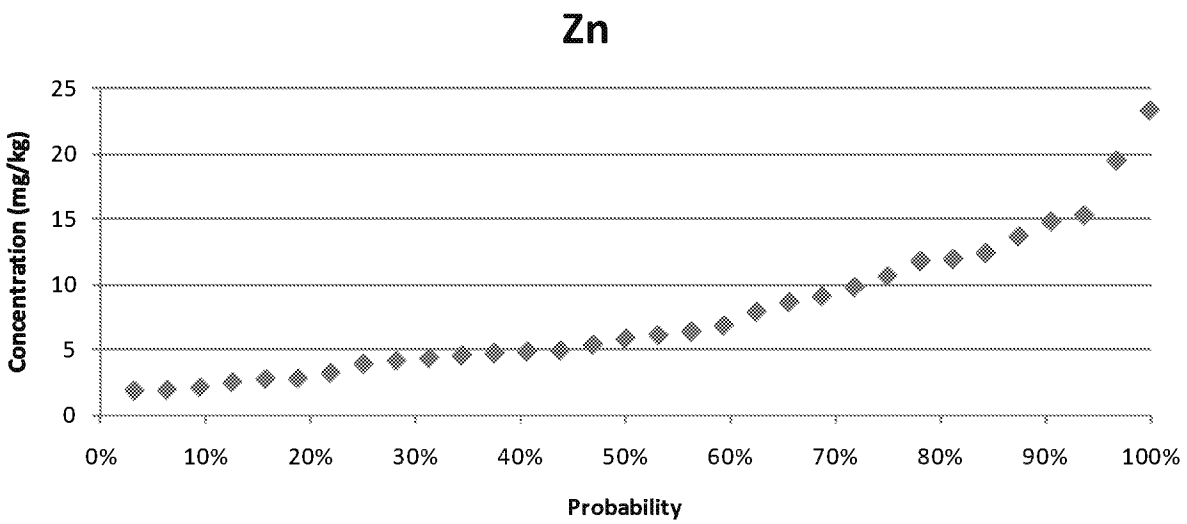

Se
Concentration (mg/kg)
35
30
25
20
15
10
5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability


Si
Concentration (mg/kg)
1200
1000
800
600
400
200
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

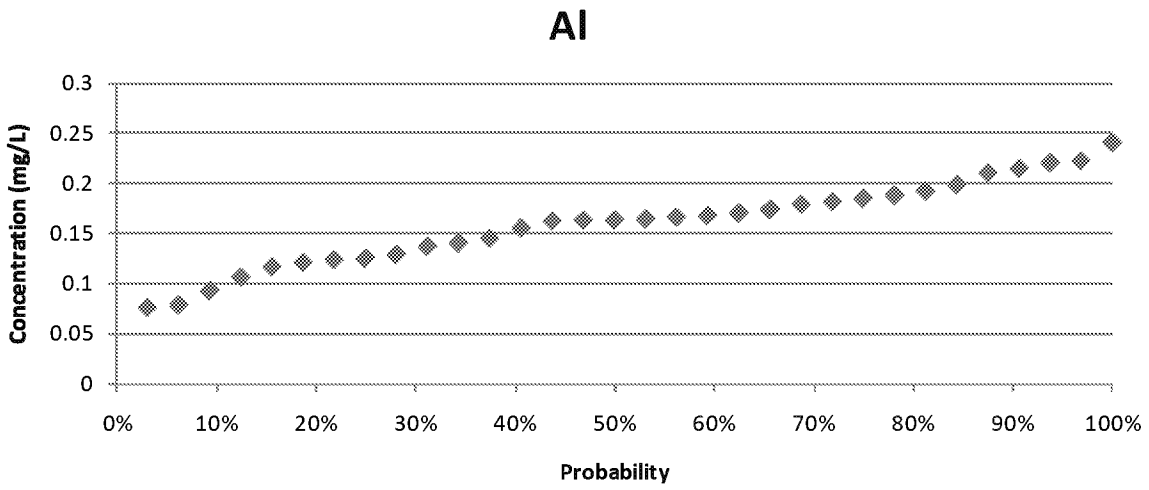

Sr
Concentration (mg/kg)
450
400
350
300
250
200
150
100
50
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

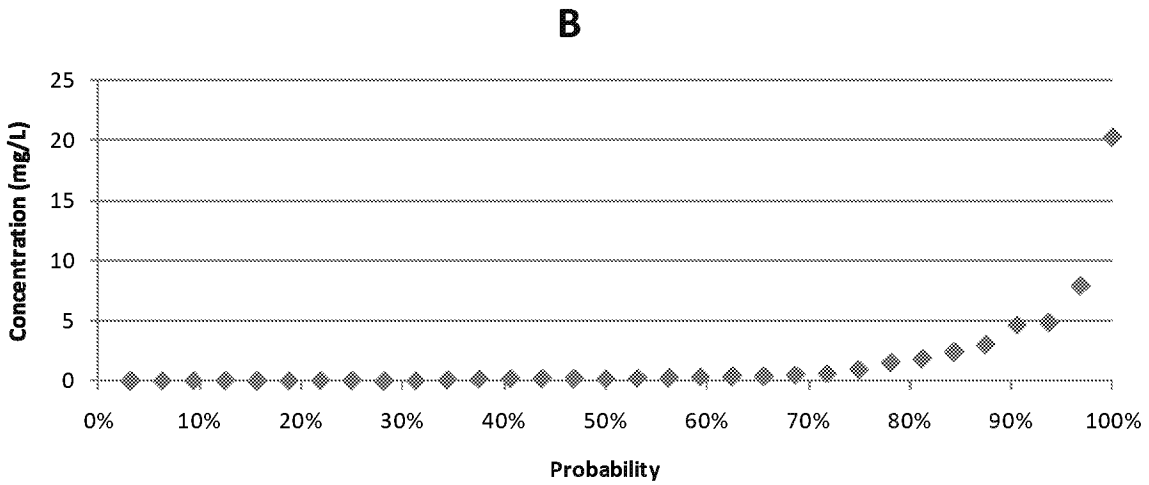

Tl
Concentration (mg/kg)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

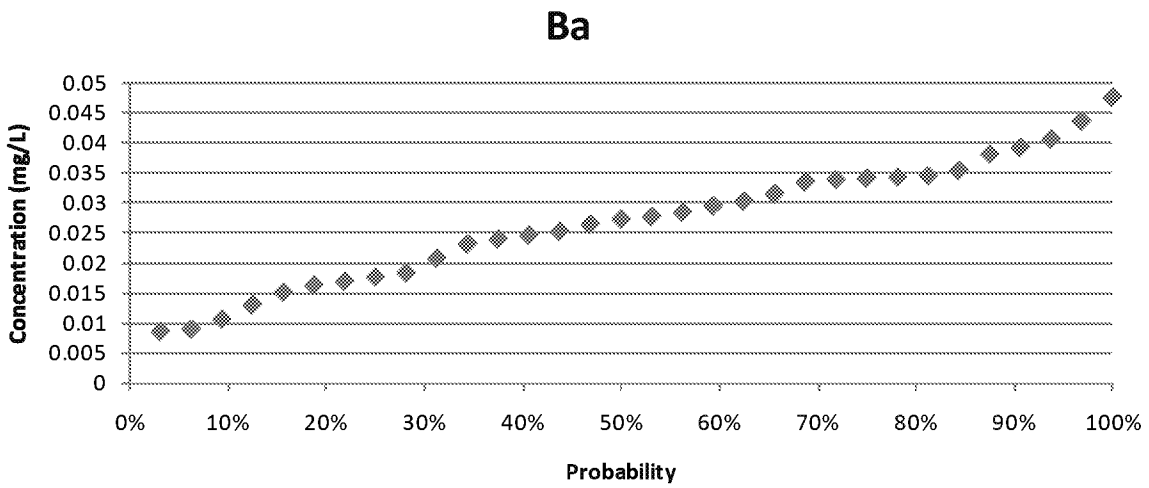

V
Concentration (mg/kg)
0
1
2
3
4
5
6
7
8
9
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

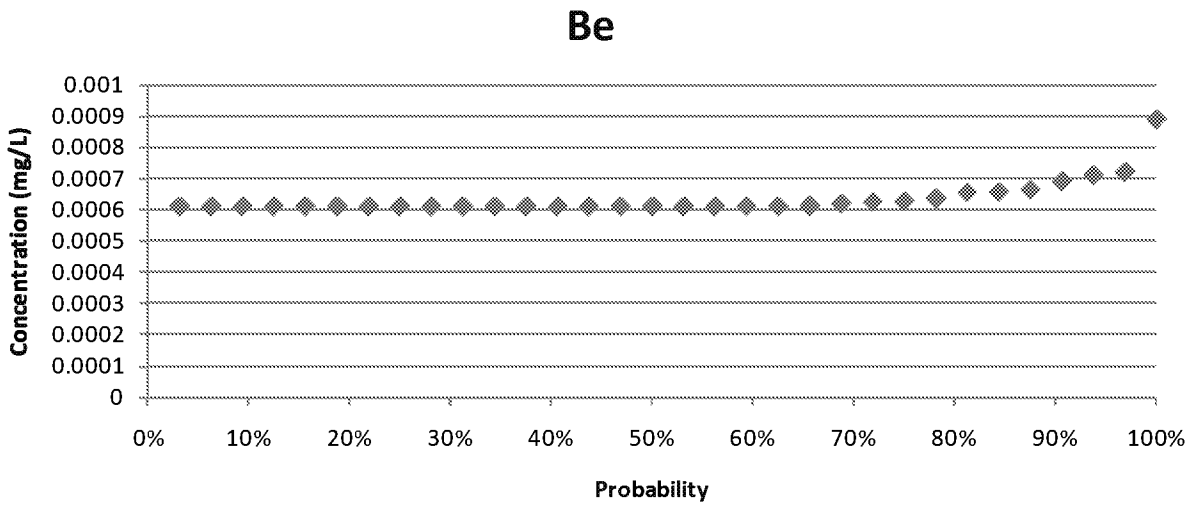

Zn
Concentration (mg/kg)
0
5
10
15
20
25
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

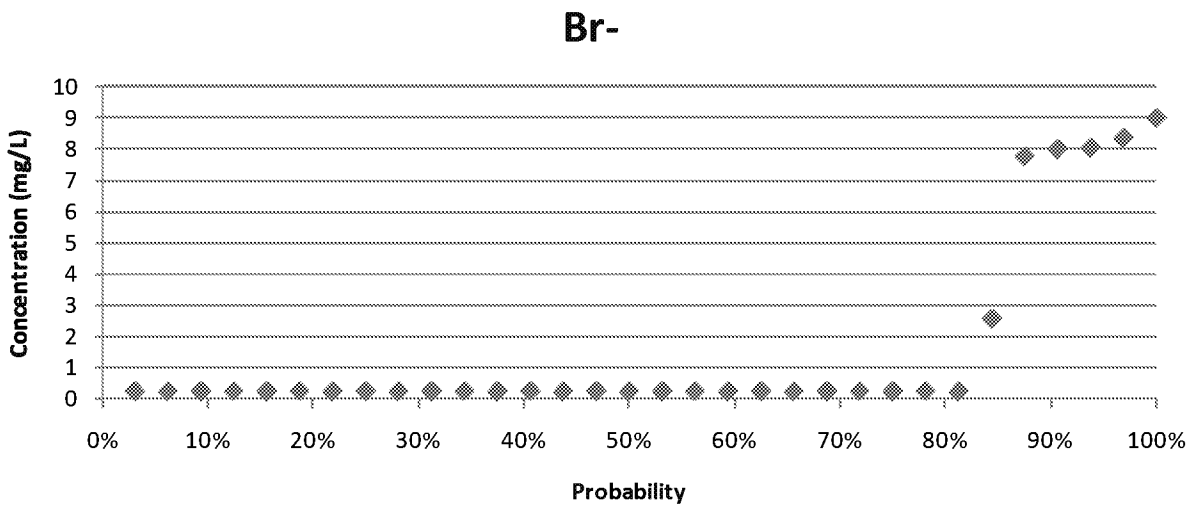
DI / SPLP

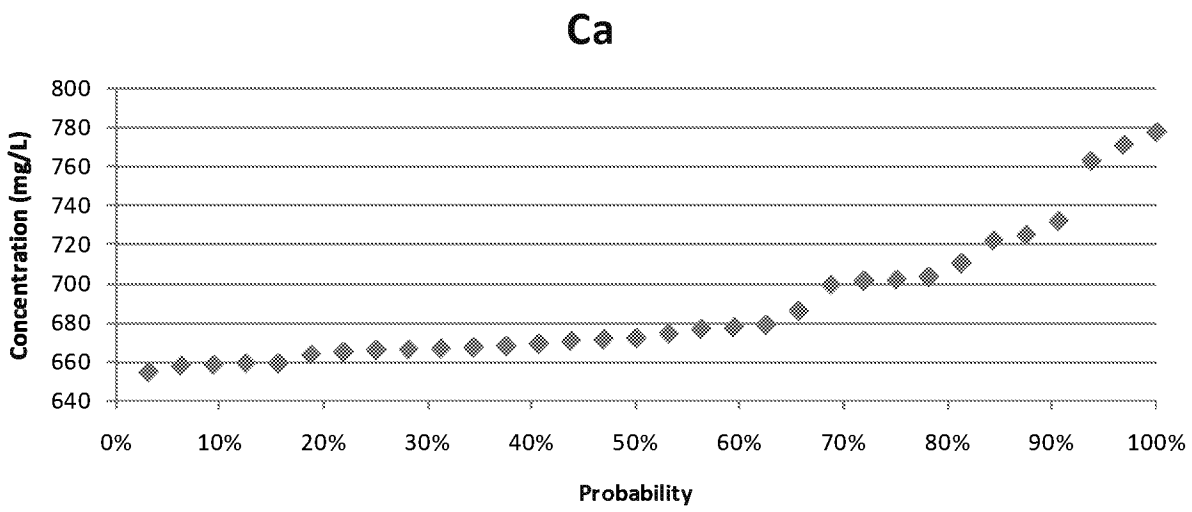

Al
Concentration (mg/L)
0.3
0.25
0.2
0.15
0.1
0.05
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

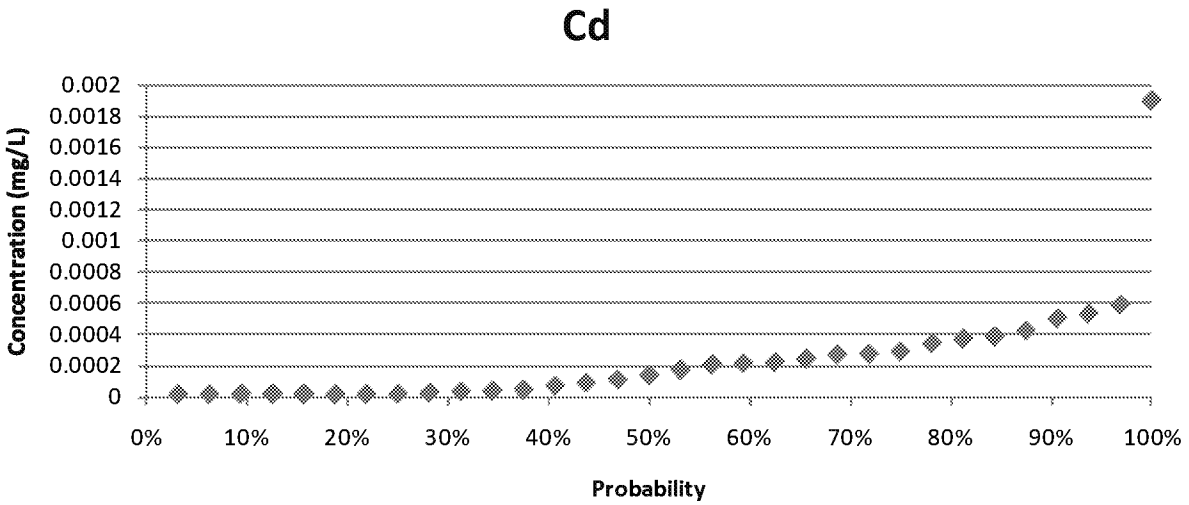

B
Concentration (mg/L)
25
20
15
10
5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

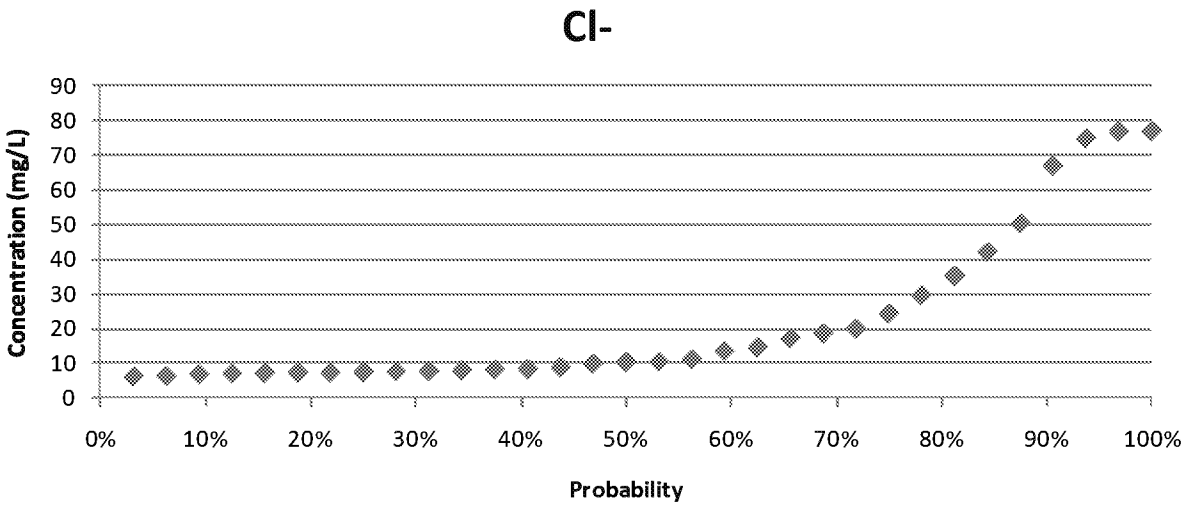

Ba
Concentration (mg/L)
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

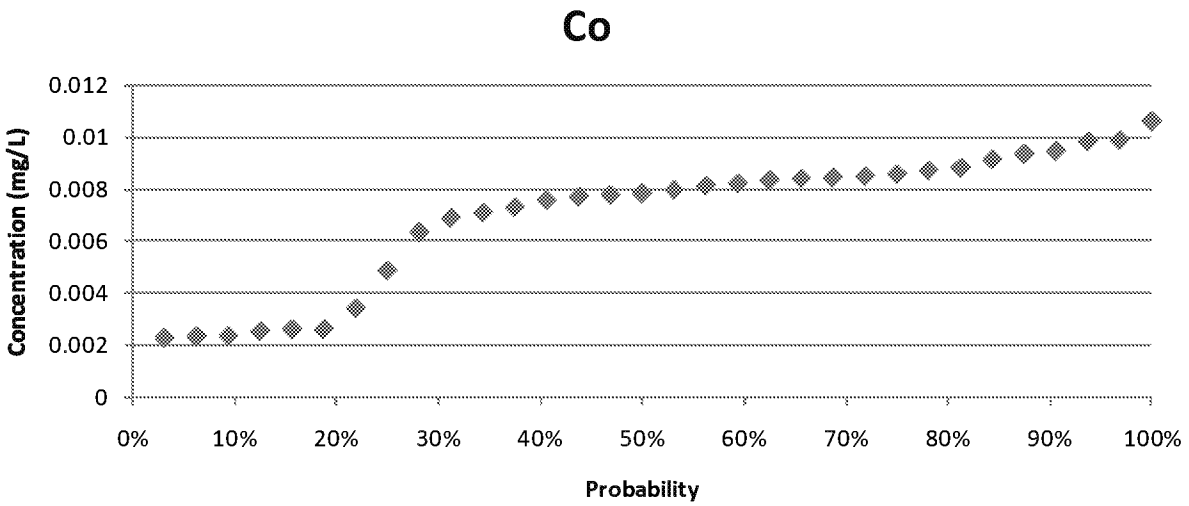

Be
Concentration (mg/L)
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

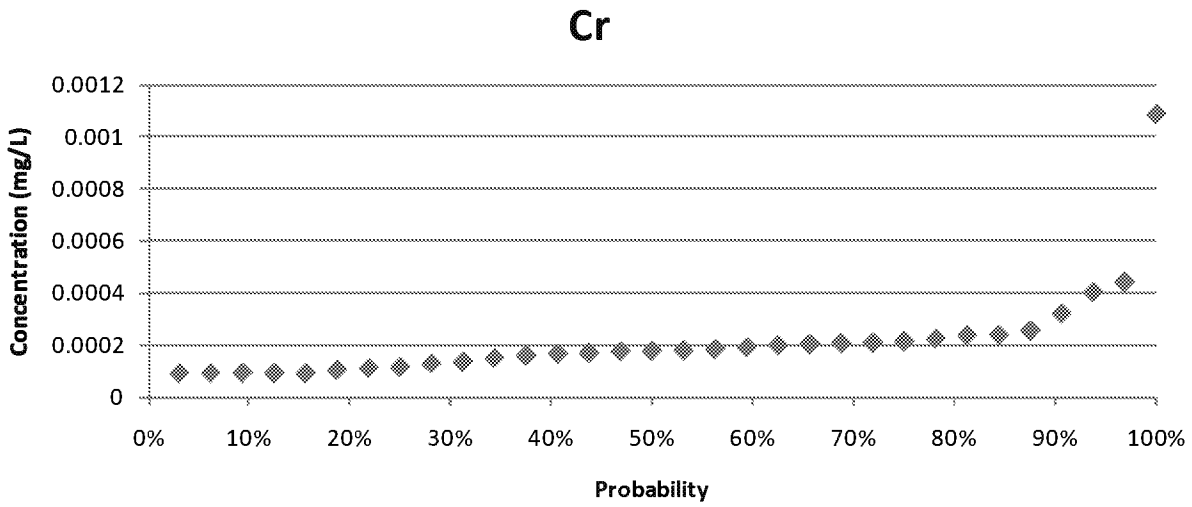

Br-
Concentration (mg/L)
10
9
8
7
6
5
4
3
2
1
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

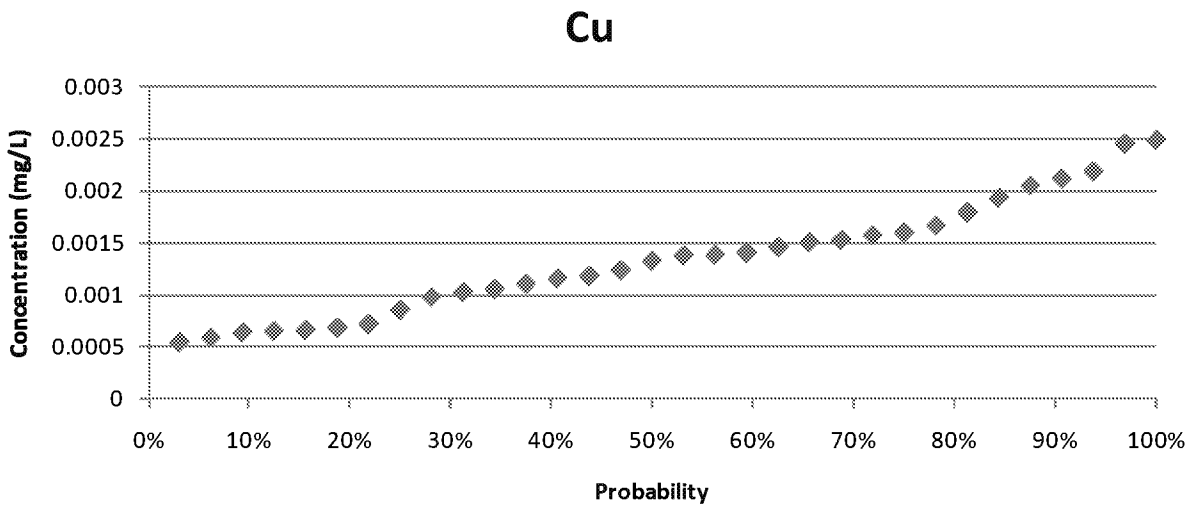

Ca
Concentration (mg/L)
800
780
760
740
720
700
680
660
640
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

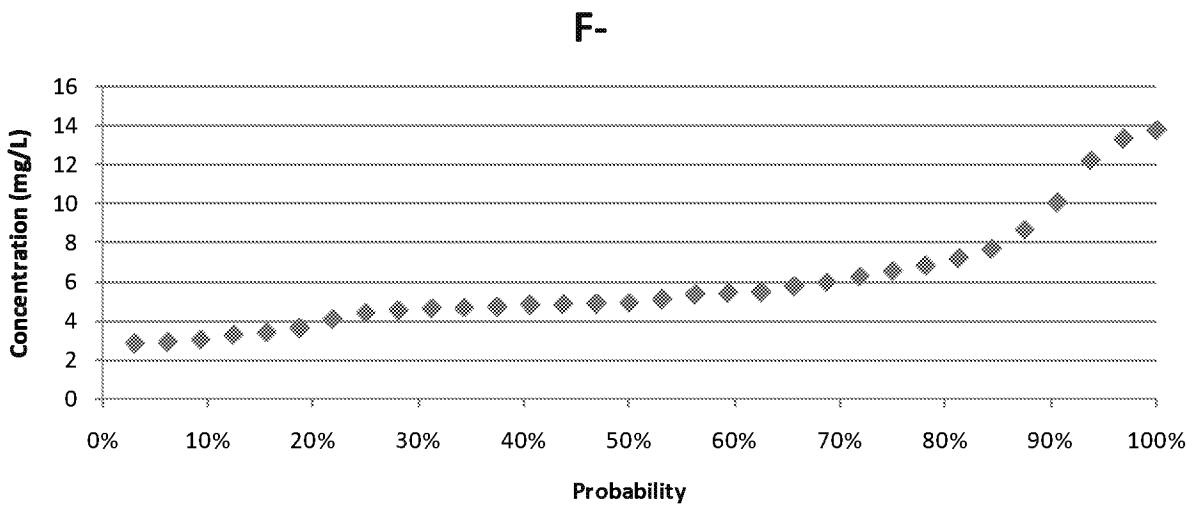

Cd
Concentration (mg/L)
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

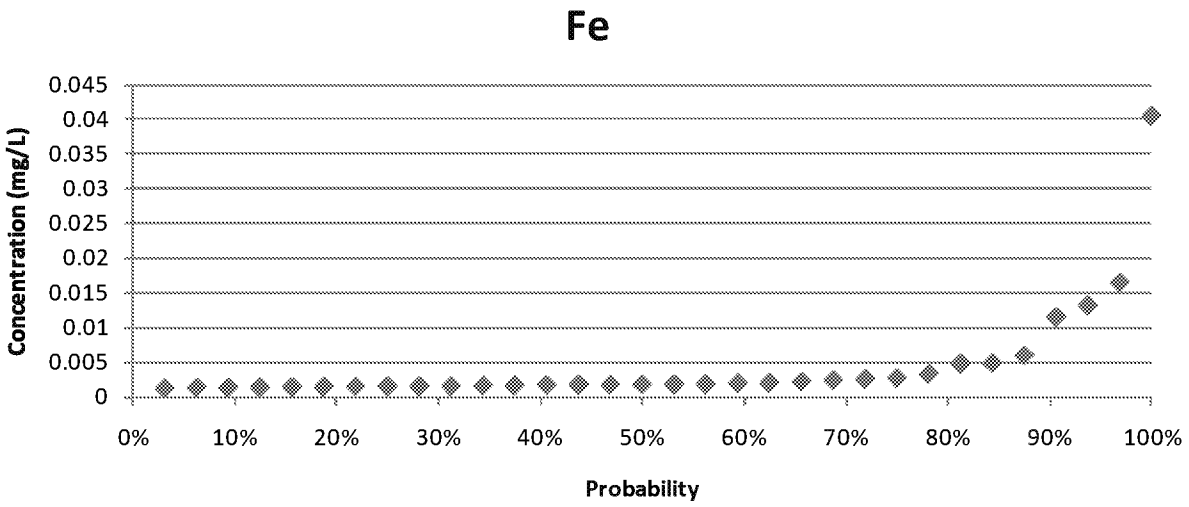

Cl-
Concentration (mg/L)
90
80
70
60
50
40
30
20
10
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

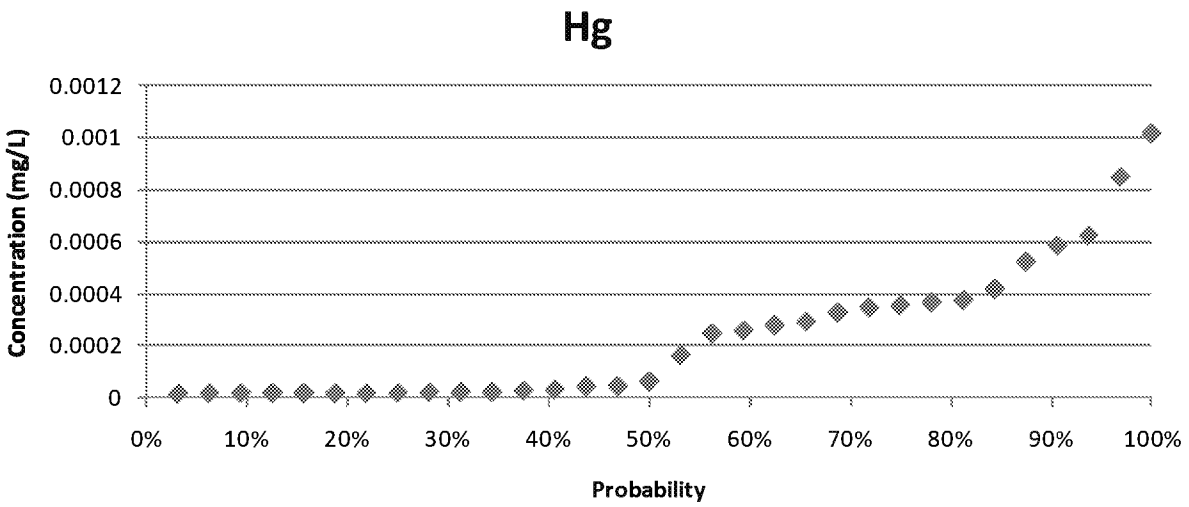

Co
Concentration (mg/L)
0.012
0.01
0.008
0.006
0.004
0.002
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

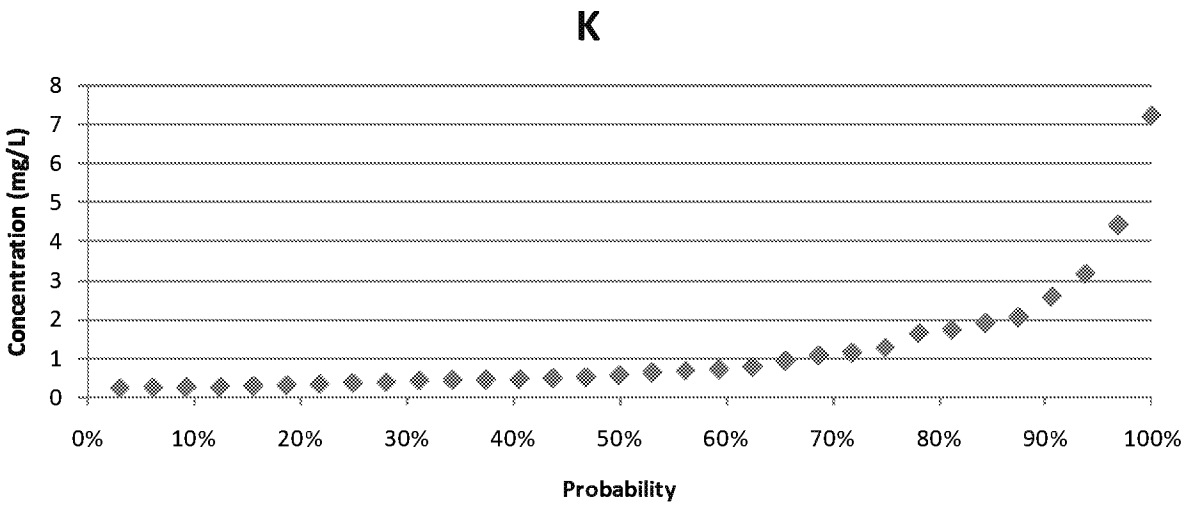

Cr
Concentration (mg/L)
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

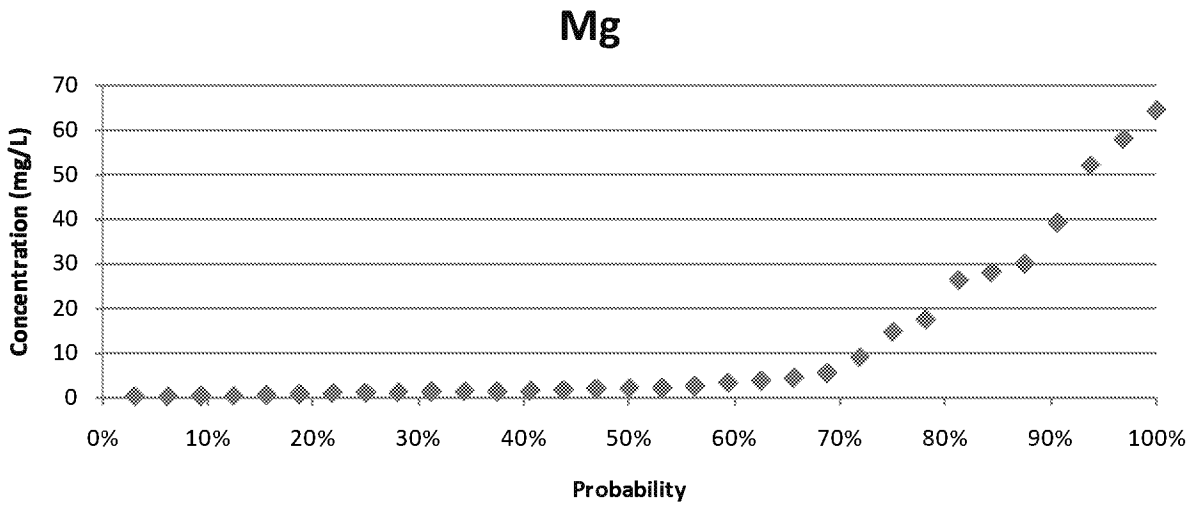

Cu
Concentration (mg/L)
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

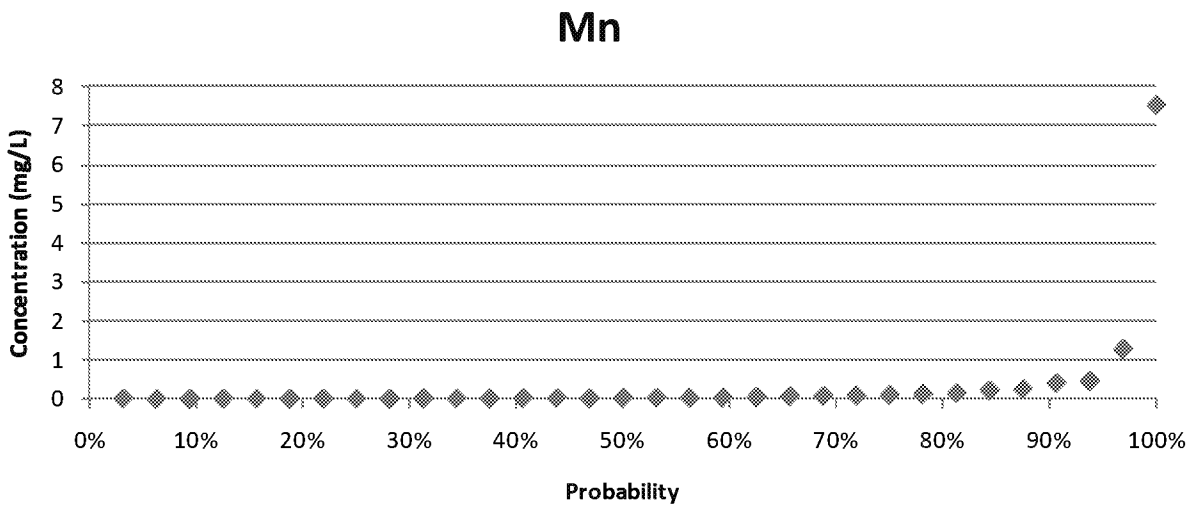

F-
Concentration (mg/L)
16
14
12
10
8
6
4
2
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

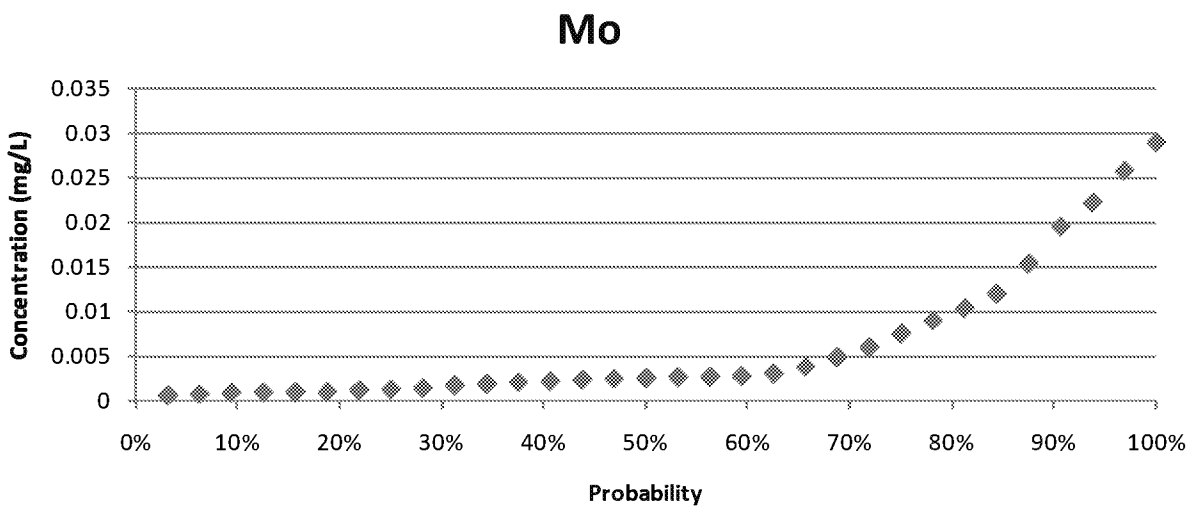

Fe
Concentration (mg/L)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

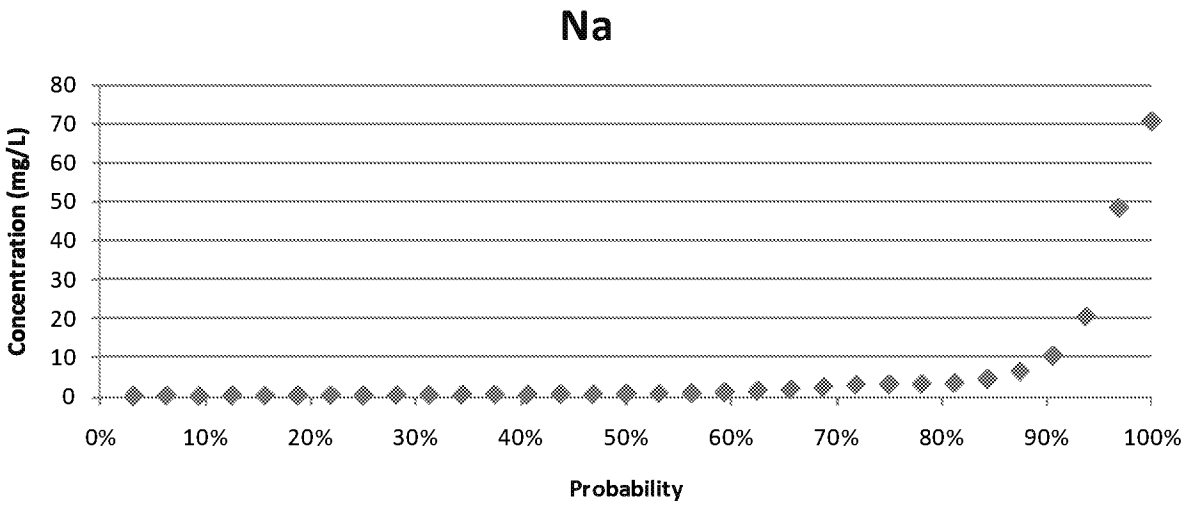

Hg
Concentration (mg/L)
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

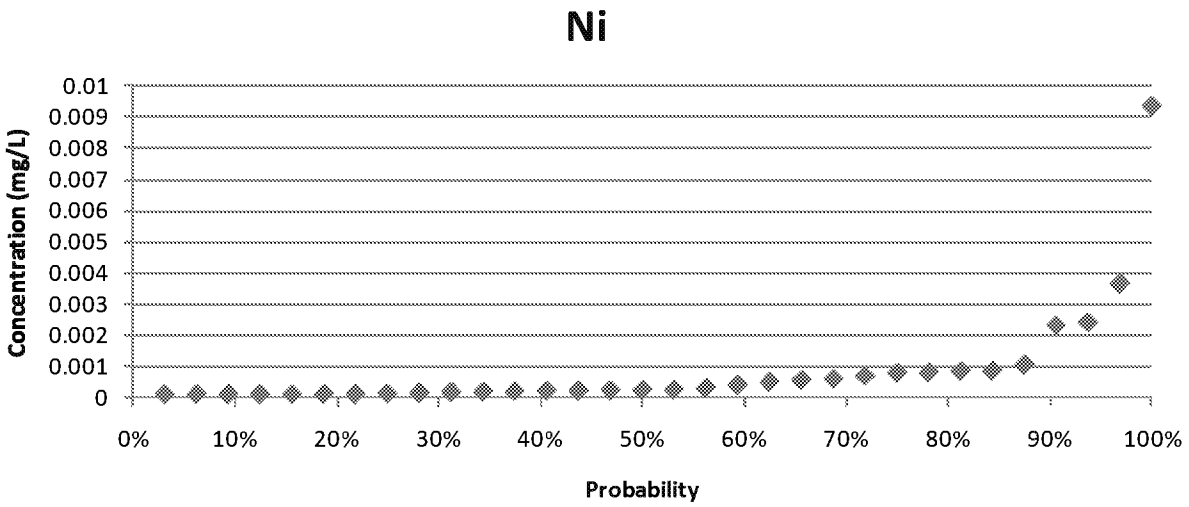

K
Concentration (mg/L)
8
7
6
5
4
3
2
1
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

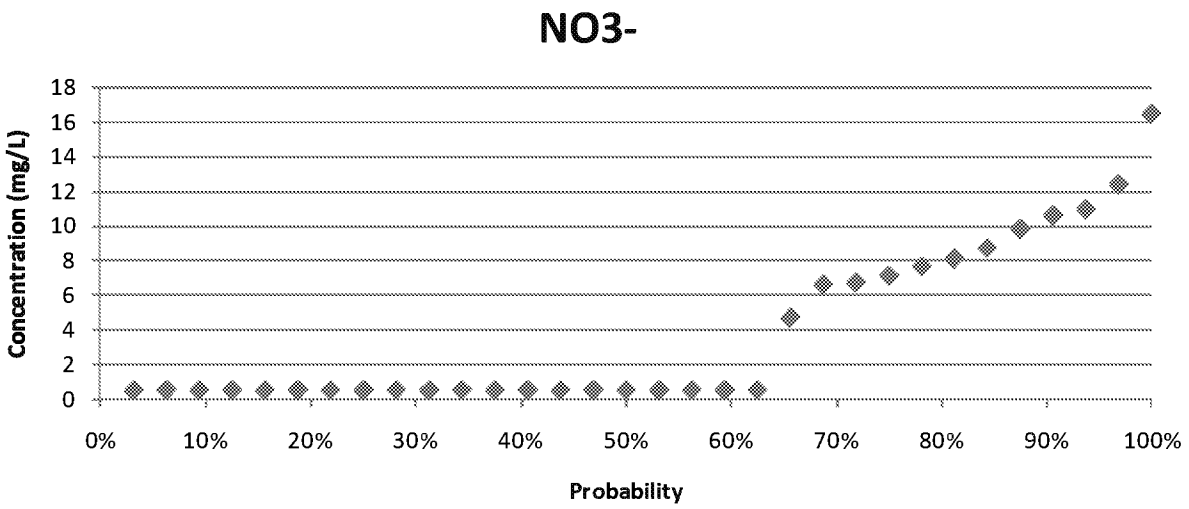

Mg
Concentration (mg/L)
70
60
50
40
30
20
10
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

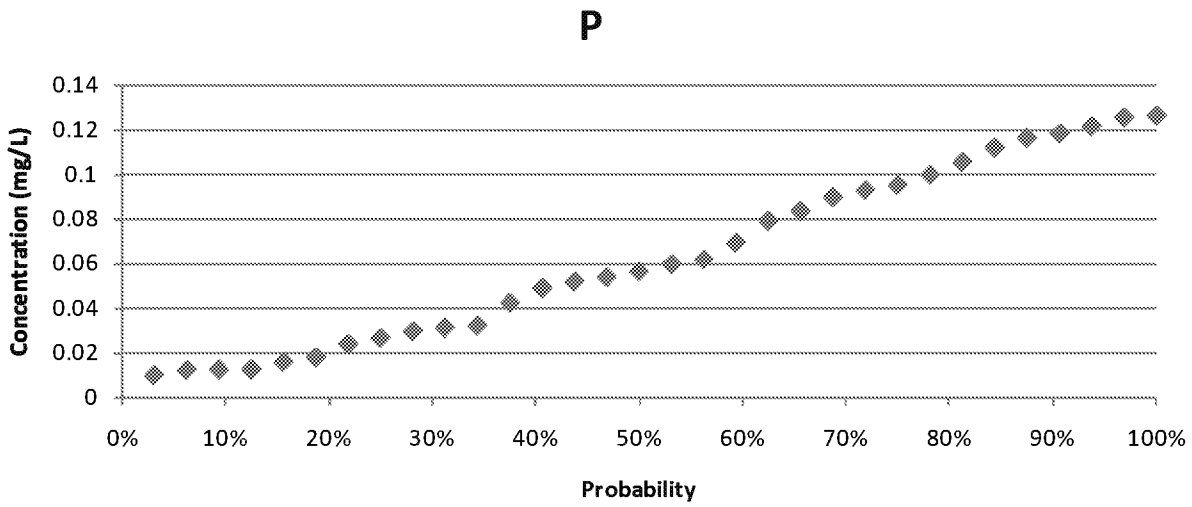

Mn
Concentration (mg/L)
8
7
6
5
4
3
2
1
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

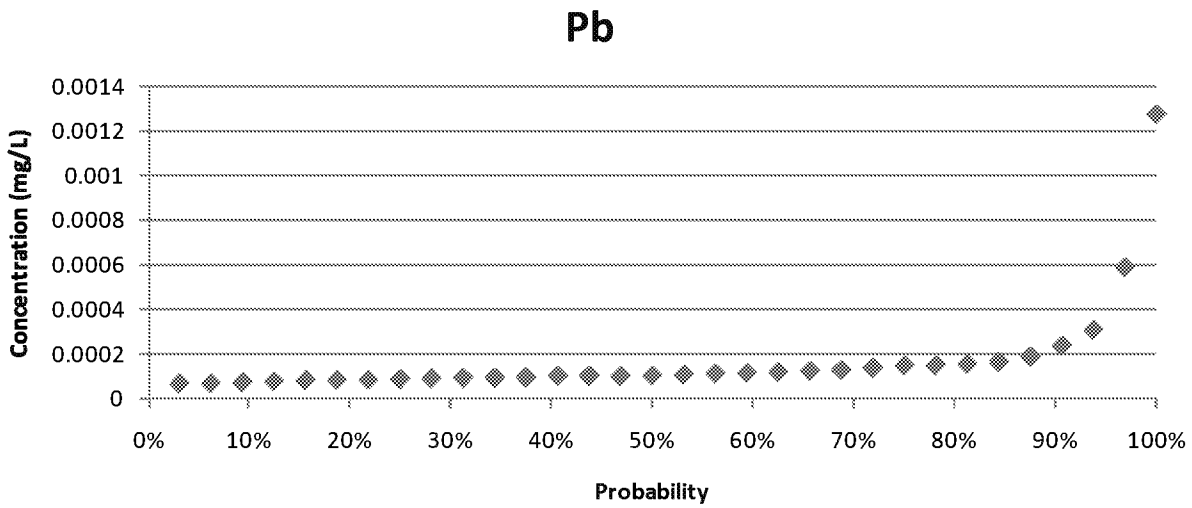

Mo
Concentration (mg/L)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

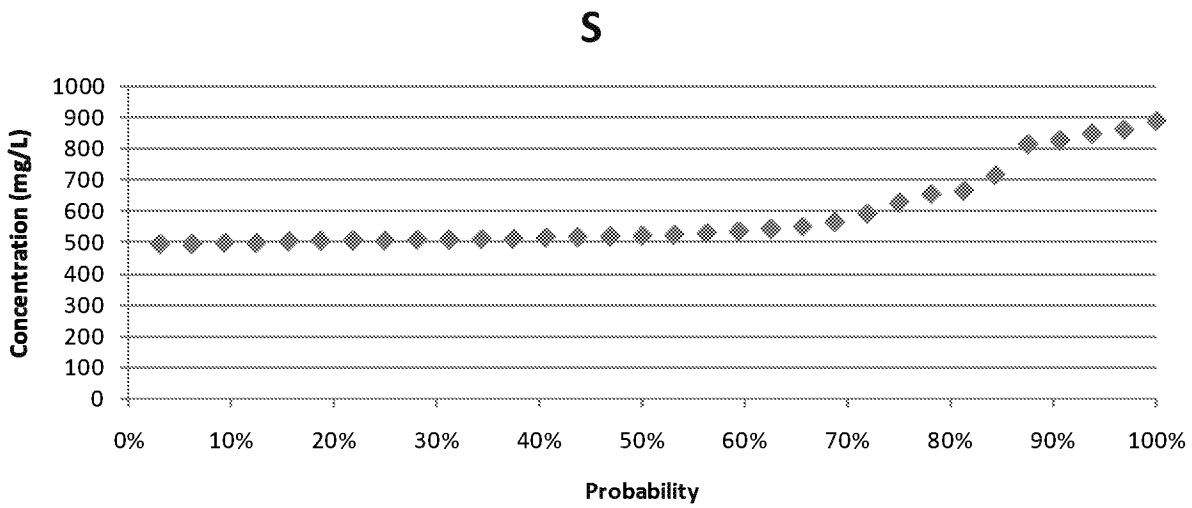

Na
Concentration (mg/L)
80
70
60
50
40
30
20
10
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

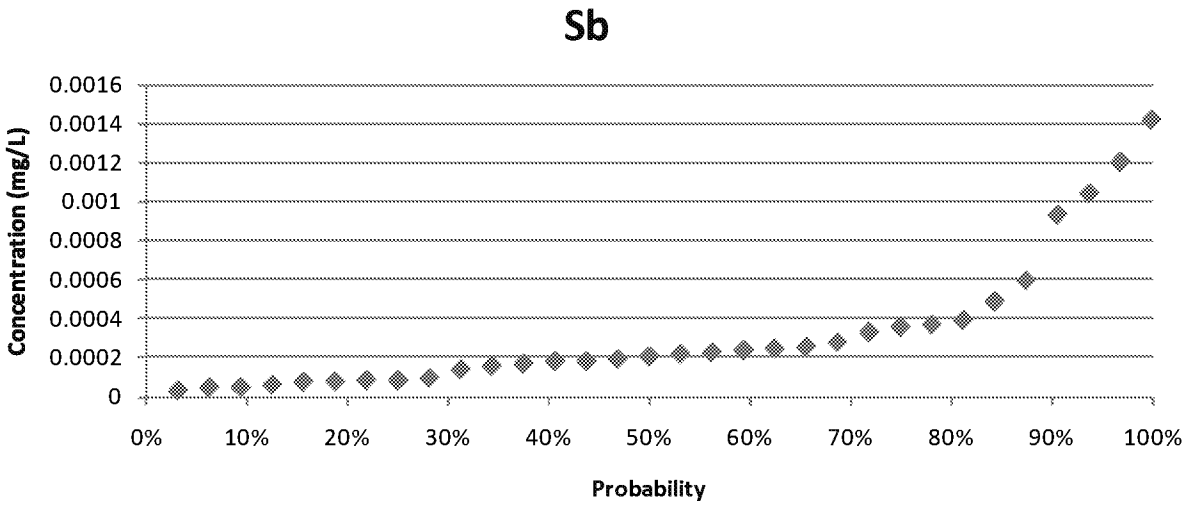

Ni
Concentration (mg/L)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

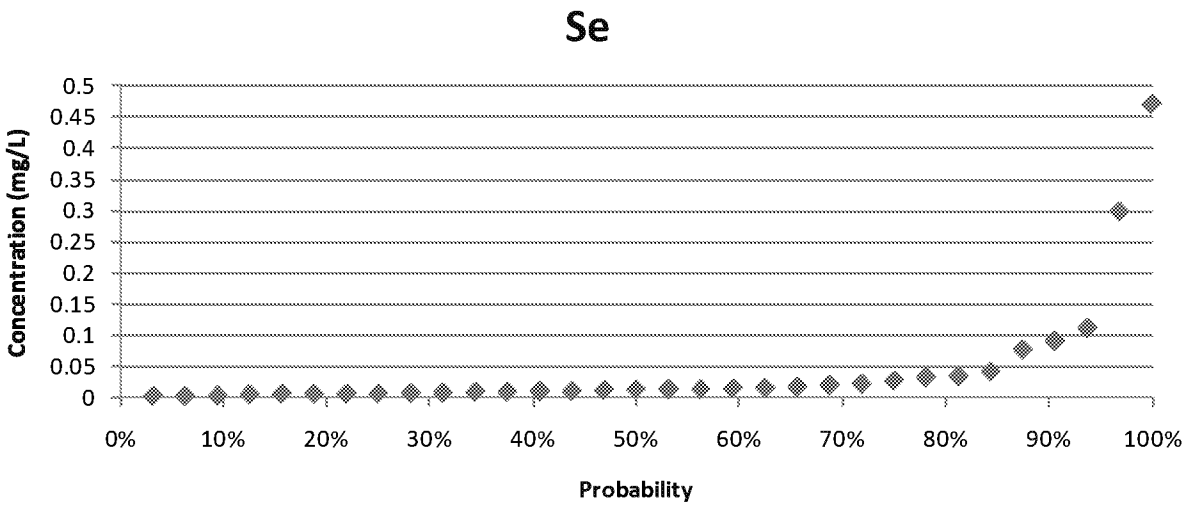

NO3-
Concentration (mg/L)
18
16
14
12
10
8
6
4
2
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

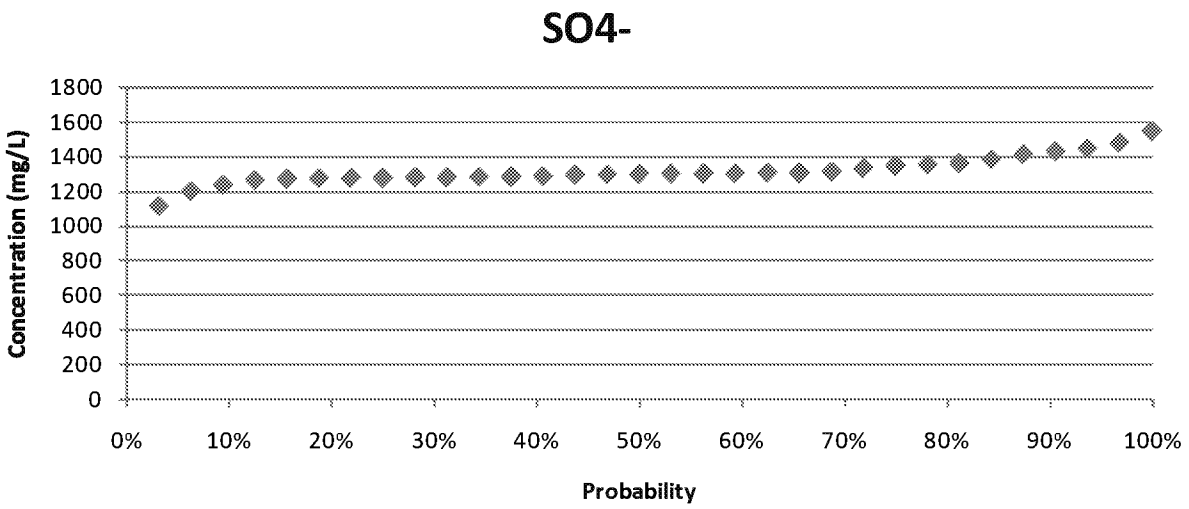

P
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Concentration (mg/L)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

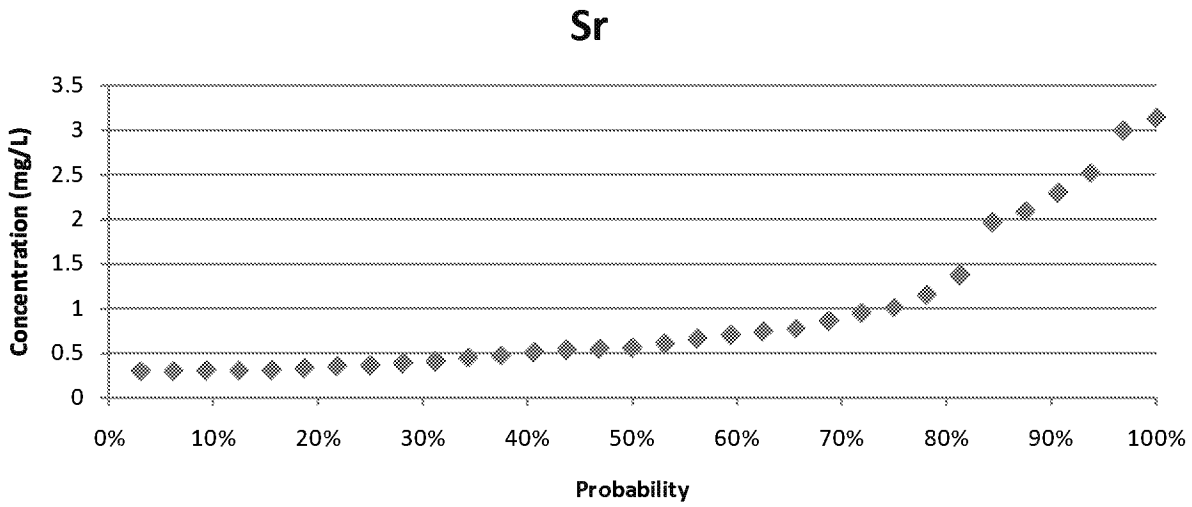

Pb
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
Concentration (mg/L)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

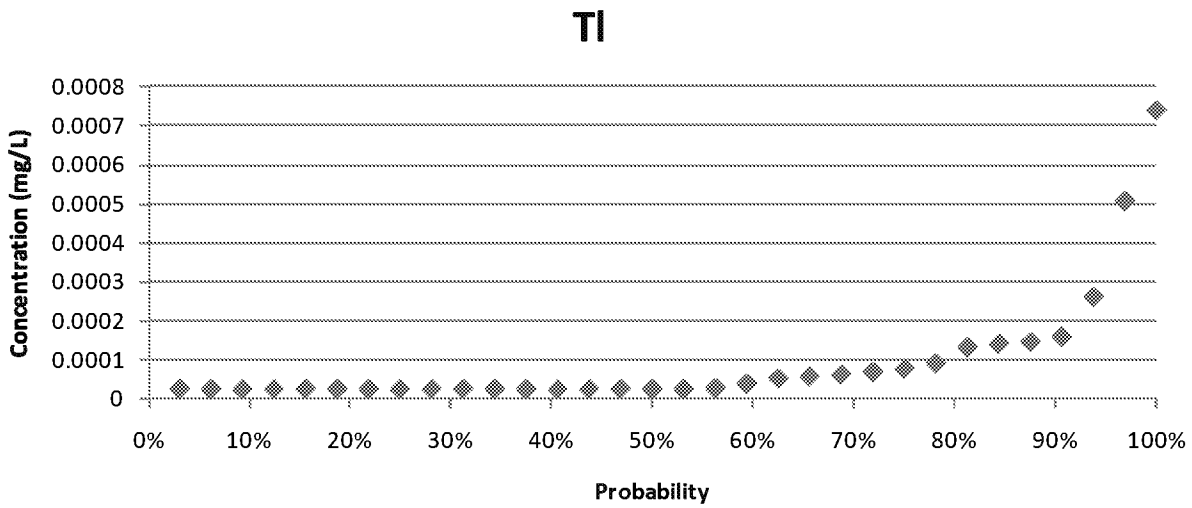

S
1000
900
800
700
600
500
400
300
200
100
0
Concentration (mg/L)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

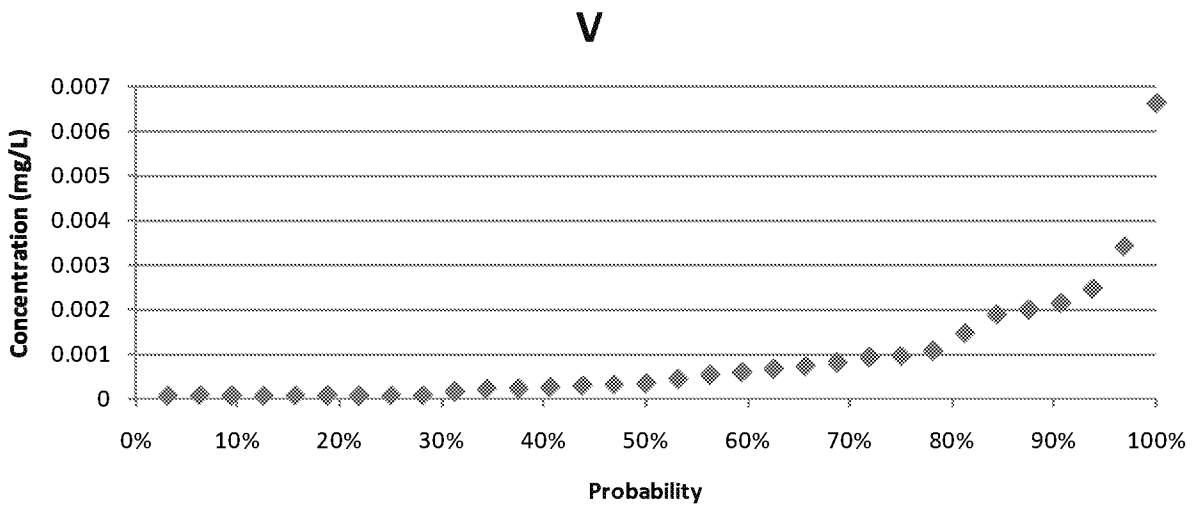

Sb
Concentration (mg/L)
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

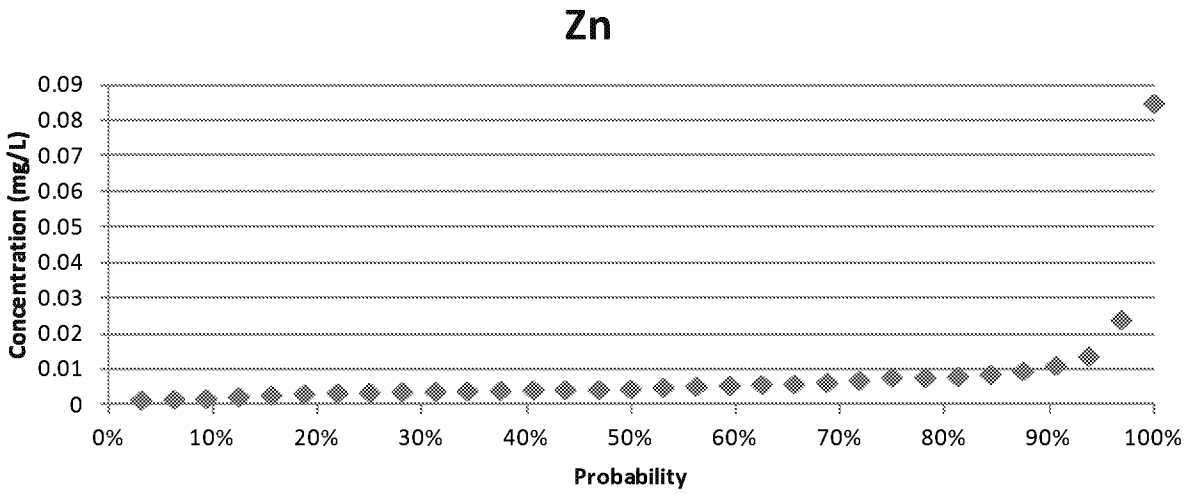

Se
Concentration (mg/L)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

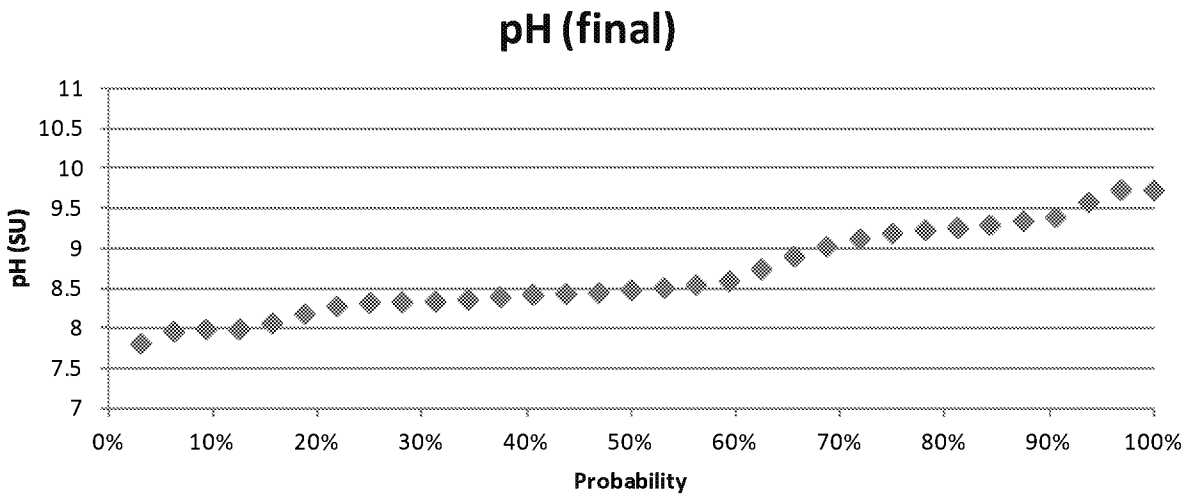

SO4-
Concentration (mg/L)
1800
1600
1400
1200
1000
800
600
400
200
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

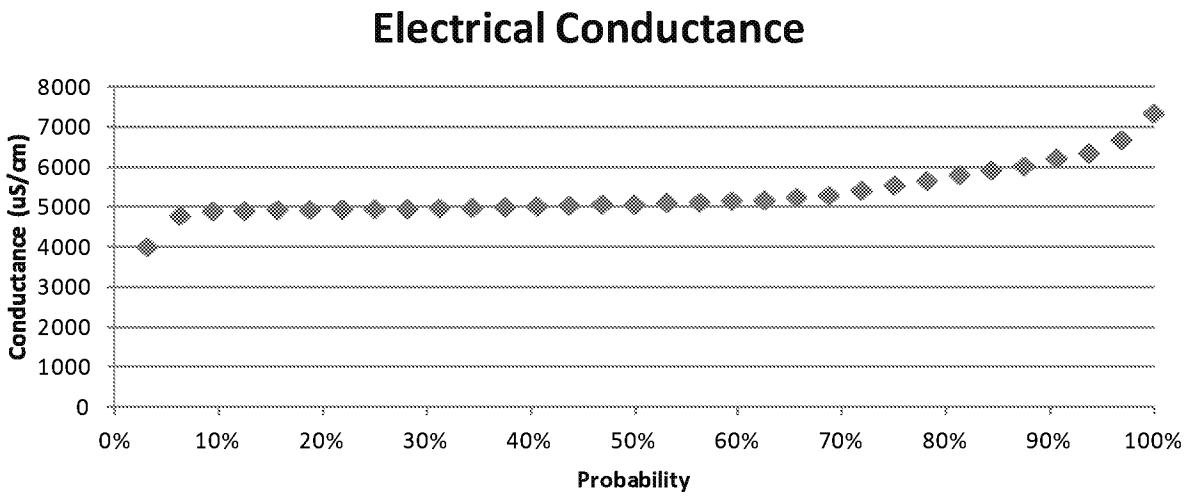

Sr
Concentration (mg/L)
3.5
3
2.5
2
1.5
1
0.5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability


Tl
Concentration (mg/L)
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability


V
Concentration (mg/L)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

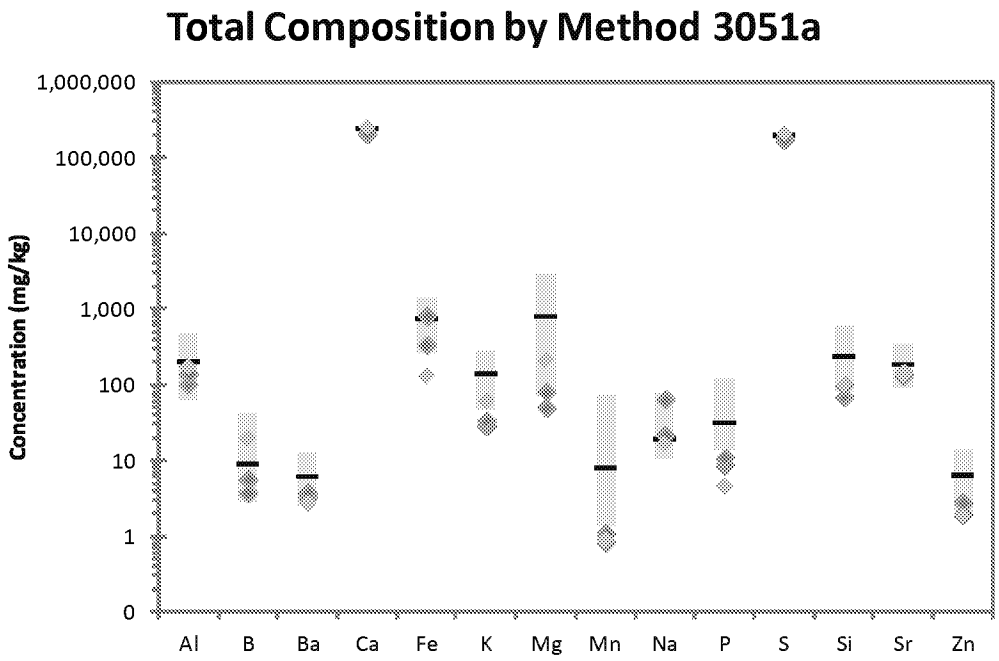

Zn
Concentration (mg/L)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

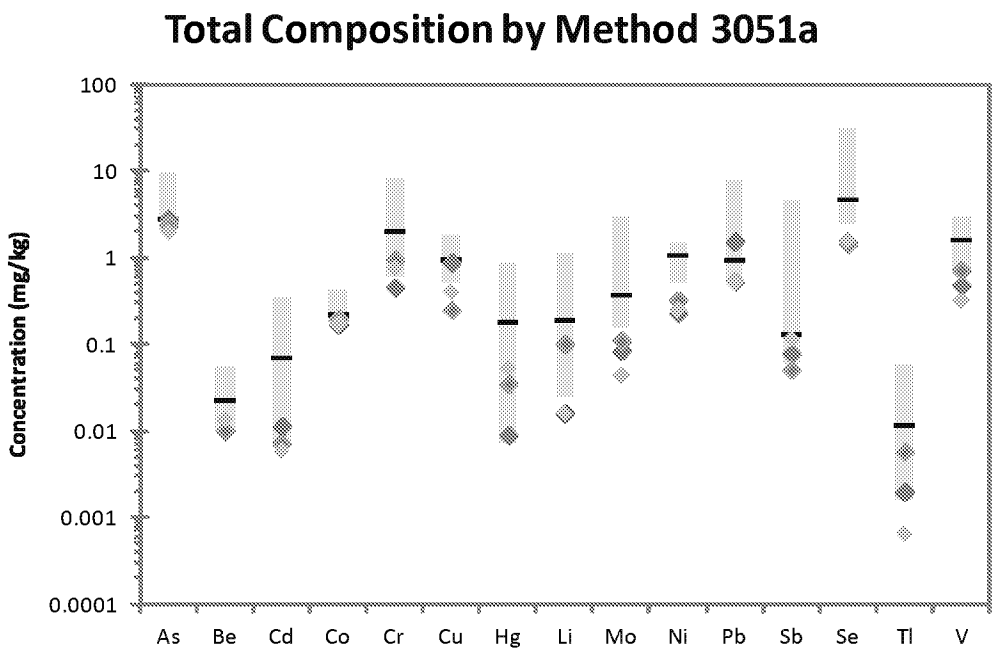

pH (final)
pH (SU)
11
10.5
10
9.5
9
8.5
8
7.5
7
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability


Electrical Conductance
Conductance (uS/cm)
8000
7000
6000
5000
4000
3000
2000
1000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability

E
ADDITIONAL DATA COMPARISONS

ED_005285_00000283-00344





Notes:
- Data for washed FGD gypsum samples

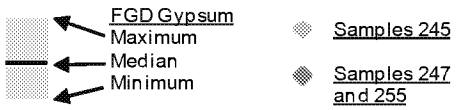
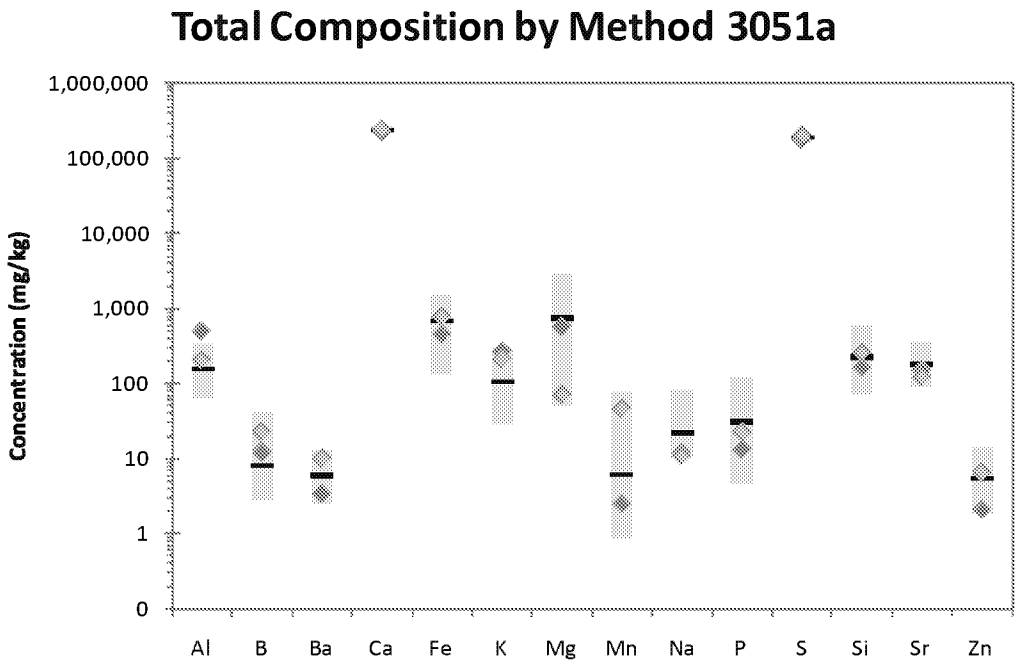
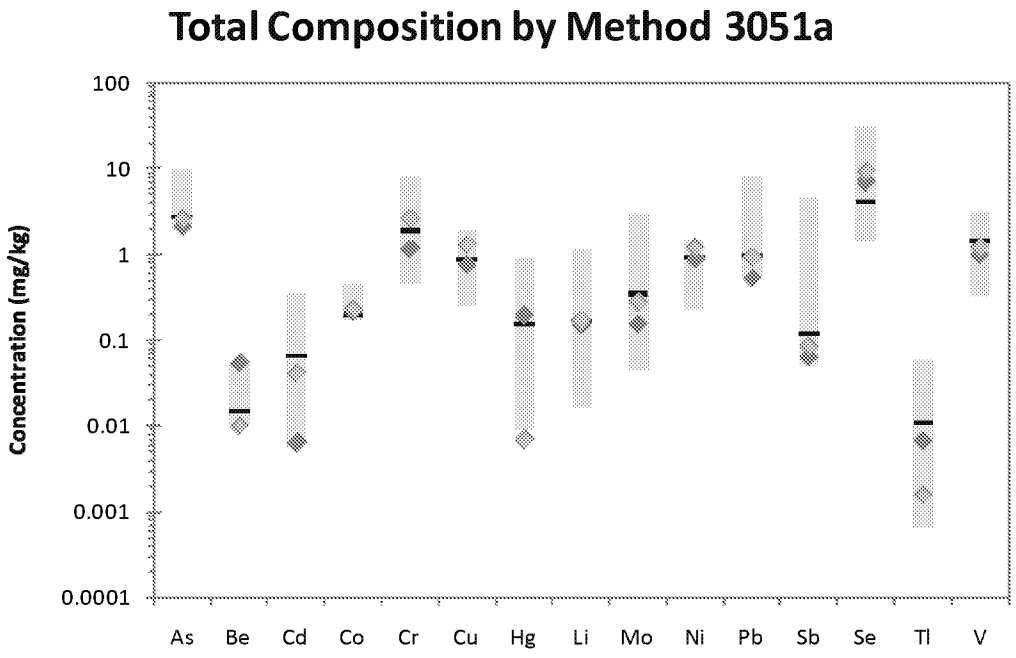


Figure E-1
Comparison of total composition for samples collected from FGD systems using lime or mag-lime as a sorbent to the samples collected from systems using limestone as a sorbent

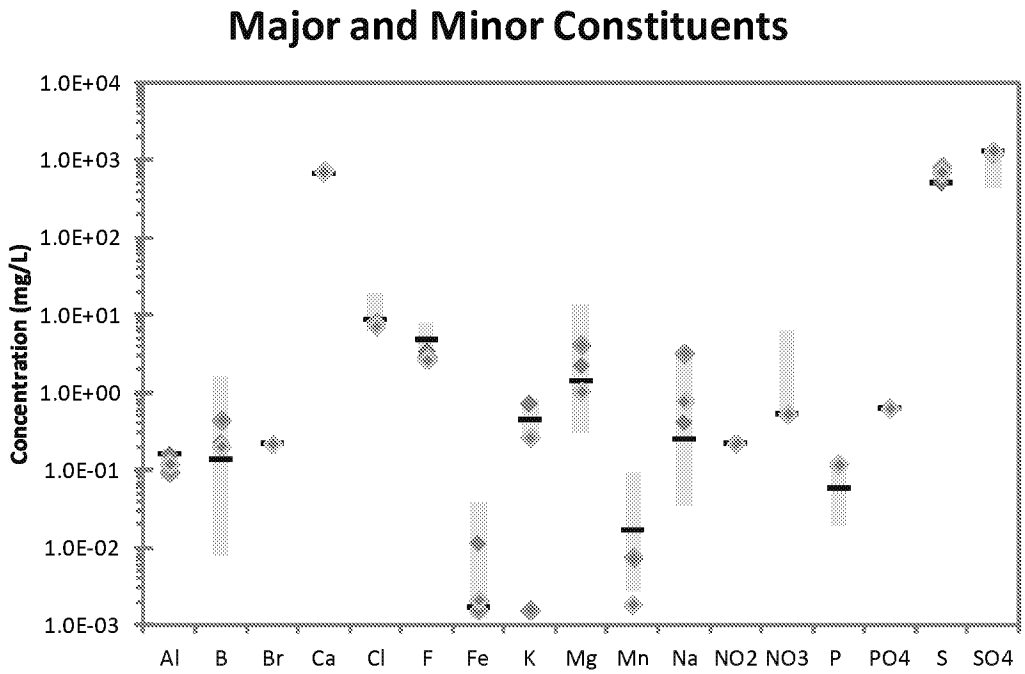
ED_005285_00000283-00345

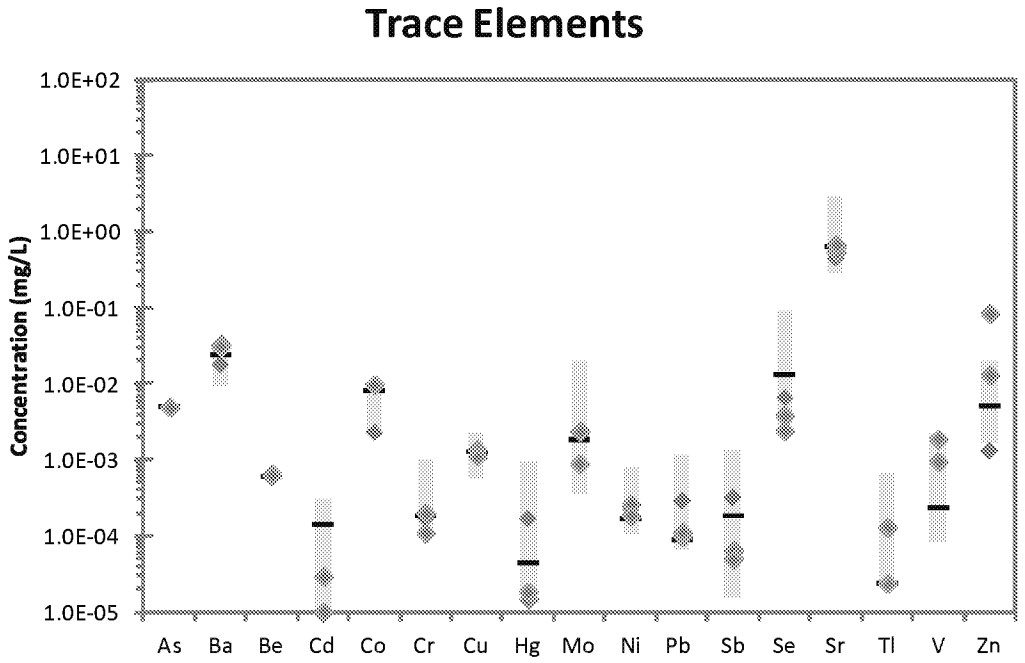




Notes:
- Data for washed samples

Figure E-2
Comparison of total composition for samples based on NOx controls





Notes:
- As, NO2, and PO4 all non-detect
- Data for washed FGD gypsum samples

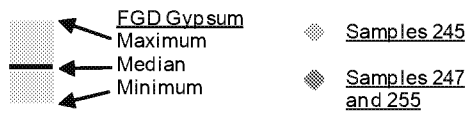


Figure E-3
Comparison of SPLP concentrations for samples collected from FGD systems using lime or mag-lime as a sorbent to the samples collected from systems using limestone as a sorbent

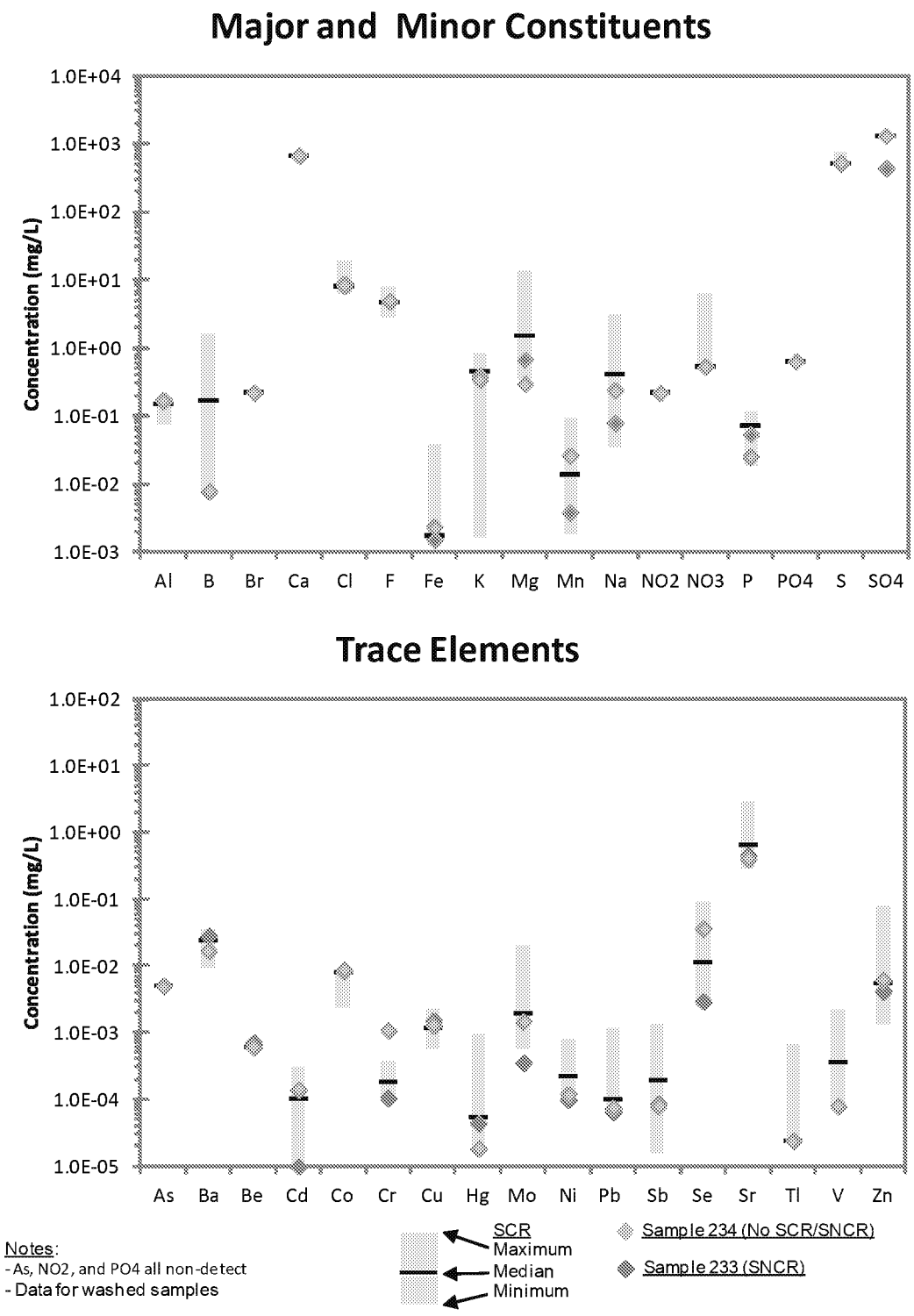


Figure E-4
Comparison of SPLP concentrations based on NOx controls

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Annals of the ICRP

Published on behalf of the International Commission on Radiological Protection

Aims and Scope

The International Commission on Radiological Protection (ICRP) is the primary body in protection against ionising radiation. ICRP is a registered charity and is thus an independent non-governmental organisation created by the 1928 International Congress of Radiology to advance for the public benefit the science of radiological protection. The ICRP provides recommendations and guidance on protection against the risks associated with ionishing radiation, from artificial sources widely used in medicine, general industry and nuclear enterprises, and from naturally occurring sources. These reports and recommendations are published four times each year on behalf of the ICRP as the journal *Annals of the ICRP*. Each issue provides in-depth coverage of a specific subject area.

Subscribers to the journal receive each new report as soon as it appears so that they are kept up to date on the latest developments in this important field. While many subscribers prefer to acquire a complete set of ICRP reports and recommendations, single issues of the journal are also available separately for those individuals and organizations needing a single report covering their own field of interest. Please order through your bookseller, subscription agent, or direct from the publisher.

ICRP is composed of a Main Commission and five standing Committees on: radiation effects, doses from radiation exposure, protection in medicine, the application of ICRP recommendations, and protection of the environment, all served by a small Scientific Secretariat. The Main Commission consists of twelve members and a Chairman. Committees typically comprise 15–20 members. Biologists and medical doctors dominate the current membership; physicists are also well represented.

ICRP uses Working Parties to develop ideas and Task Groups to prepare its reports. A Task Group is usually chaired by an ICRP Committee member and usually contains a majority of specialists from outside ICRP. Thus, ICRP is an independent international network of specialists in various fields of radiological protection. At any one time, about one hundred eminent scientists are actively involved in the work of ICRP. The Task Groups are assigned the responsibility for drafting documents on various subjects, which are reviewed and finally approved by the Main Commission. These documents are then published as the *Annals of the ICRP*.

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PUBLICATION 103

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The 2007 Recommendations of the International Commission on Radiological Protection

ICRP Publication 103

Approved by the Commission in March 2007

Abstract–These revised Recommendations for a System of Radiological Protection formally replace the Commission's previous, 1990, Recommendations; and update, consolidate, and develop the additional guidance on the control of exposure from radiation sources issued since 1990.

Thus, the present Recommendations update the radiation and tissue weighting factors in the quantities equivalent and effective dose and update the radiation detriment, based on the latest available scientific information of the biology and physics of radiation exposure. They maintain the Commission's three fundamental principles of radiological protection, namely justification, optimisation, and the application of dose limits, clarifying how they apply to radiation sources delivering exposure and to individuals receiving exposure.

The Recommendations evolve from the previous process-based protection approach using practices and interventions by moving to an approach based on the exposure situation. They recognise planned, emergency, and existing exposure situations, and apply the fundamental principles of justification and optimisation of protection to all of these situations. They maintain the Commission's current individual dose limits for effective dose and equivalent dose from all regulated sources in planned exposure situations. They re-inforce the principle of optimisation of protection, which should be applicable in a similar way to all exposure situations, subject to the following restrictions on individual doses and risks; dose and risk constraints for planned exposure situations, and reference levels for emergency and existing exposure situations. The Recommendations also include an approach for developing a framework to demonstrate radiological protection of the environment.
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Keywords: Justification; Optimisation; Dose limits; Constraints; Reference Levels

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Annals of the ICRP

Editorial

WE COULD NOT HAVE DONE IT WITHOUT YOUR HELP

The new recommendations of the International Commission on Radiological Protection were adopted on 21 March 2007, Essen, Germany, after eight years of discussions, involving scientists, regulators, and users all around the world.

The Commission is an advisory body that offers its recommendations to regulatory and advisory agencies, mainly by providing guidance on the fundamental principles on which appropriate radiological protection can be based. Since its inception in 1928, the Commission has regularly issued recommendations regarding protection against the hazards of ionising radiation. The first report in the current series, *Publication 1,* contained the recommendations adopted in 1958 (ICRP, 1959). The more recent recommendations have appeared as *Publication 26* (ICRP, 1977), and *Publication 60* (ICRP, 1991b), and contain the recommendations adopted in 1977 and 1990, respectively.

International organisations and national authorities responsible for radiological protection, as well as the users, have taken the recommendations and principles issued by the Commission as a key basis for their protective actions. As such, virtually all international standards and national regulations addressing radiological protection are based on the Commission's recommendations.

Currently, most national regulations are based on the 1990 Recommendations in *Publication 60*. International standards, such as the International Basic Safety Standards, various international labour conventions, and European directives on radiological protection are also based on these recommendations.

In *Publication 26*, the Commission quantified the risks of stochastic effects of radiation and proposed a system of dose limitation with its three principles of justification, optimisation of protection, and individual dose limitation. In *Publication 60*, the Commission revised its recommendations and extended its philosophy to a system of radiological protection while keeping the fundamental principles of protection.

New scientific data have been published since *Publication 60*, and while the biological and physical assumptions and concepts remain robust, some updating is required. The overall estimate of deterministic effects remain fundamentally the same. The estimates of cancer risk attributable to radiation exposure have not changed greatly in the past 17 years, whereas the estimated risk of heritable effects is currently lower than before. The new data provide a firmer basis on which to model risks and assess detriment.

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The 2007 Recommendations evolve from the previous process-based approach of practices and interventions to an approach based on the characteristics of radiation exposure situations. The system of radiological protection applies in principle to any situation of radiation exposure. Similar procedures are used for deciding on the extent and level of protective actions, regardless of exposure situation. Specifically, the principles of justification and optimisation apply universally. ICRP is of the opinion that by focusing more on optimisation, the implementation of protection for what has until now been categorised as interventions could be enhanced.

In view of the importance afforded to the Commission's recommendations and to ensure that the new recommendations adequately and appropriately address national issues and concerns, the Commission has initiated a much more open process than that used for the development of the previous recommendations. It should also be noted that the Commission mentions, for the first time, the need to account for the views and concerns of stakeholders when optimising protection.

The Commission has therefore solicited input from a broad spectrum of radiological protection stakeholders, ranging from government institutions and international organisations to scientists and non-governmental organisations. The draft recommendations have been discussed at a large number of international and national conferences and by the many international and national organisations with an interest in radiological protection.

Many of these also arranged particular activities around the Recommendations project. Thus for instance, the International Radiation Protection Association arranged reviews through its member organisations world-wide for their 2000 and 2004 Congresses and in connection with our 2006 public consultation, the Nuclear Energy Agency of the OECD organised seven international workshops and performed four detailed assessments of draft ICRP texts (in 2003, 2004, 2006, and 2007), and the European Commission organised a seminar in 2006 to debate the scientific issues in the Recommendations. The United Nations agencies, with the International Atomic Energy Agency as the lead agency, are using the 2007 ICRP Recommendations as a major input to their project of revising the International Basic Safety Standards, and likewise the European Commission uses the 2007 Recommendations as a major input to their revision of the European Basic Safety Standards.

The Recommendations have been prepared after two phases of international public consultation. By following this policy of transparency and involvement of stakeholders, ICRP is expecting a clearer understanding and wide acceptance of its Recommendations. Although the revised Recommendations do not contain any fundamental changes to the radiological protection policy, they will help to clarify application of the system of protection in the plethora of exposure situations encountered, thereby improving the already high standards of protection.

The Commission is pleased at having arrived at the end of a long but useful gestation phase including numerous consultations and is proud to present these 2007 Recommendations. The extensive consultations resulted in a much improved document and the Commission is grateful to the many organisations, experts, and individual members of the public who have devoted so much of their time and

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experience to helping us to improve the Recommendations. Their contributions have been crucial for the future success of the 2007 Recommendations.

LARS-ERIK HOLM
CHAIRMAN, ICRP

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PREFACE

Since issuing its 1990 Recommendations as ICRP *Publication 60* (ICRP 1991b), the Commission has reviewed these Recommendations regularly and, from time to time, has issued supplementary reports in the *Annals of the ICRP*. The extent of these supplementary reports has indicated the need for the consolidation and rationalisation presented here. New scientific data have also been published since *Publication 60*, and while the biological and physical assumptions and concepts remain robust, some updating is required. The overall estimates of deterministic effects and stochastic risk remain fundamentally the same. The overall estimates of cancer risk attributable to radiation exposure have not changed appreciably in the past 16 years. Conversely, the estimated risk of heritable effects is currently lower than before. Overall, the new data provide a firmer basis on which to model risks and assess detriment. Finally, it has also become apparent that the radiological protection of the environment should receive more emphasis than in the past.

Therefore, while recognising the need for stability in international and national regulations, the Commission has decided to issue these revised Recommendations having two primary aims in mind:

- to take account of new biological and physical information and of trends in the setting of radiation safety standards; and
- to improve and streamline the presentation of the Recommendations.

In addition, the Commission has maintained as much stability in the Recommendations as is consistent with the new scientific information and societal expectations.

In its revised System of Protection, the Recommendations of the Commission now evolve from the previous process-based approach of practices and interventions to an approach based on the characteristics of radiation exposure situations. In taking this approach, the Commission wishes to affirm that its system of protection can be applied in principle to any situation of radiation exposure. Similar procedures are used for deciding on the extent and level of protective actions, regardless of exposure situation. Specifically, the principles of justification and optimisation apply universally. The Commission is of the opinion that the implementation of protection for what has until now been categorised as interventions could be enhanced by increasing the attention to these common features.

These Recommendations were produced by the Main Commission of ICRP, based on an earlier draft that was subjected to public and internal consultation in 2004 and again, in revised form, in 2006. By introducing more transparency and by involving the many organisations and individuals having an interest in radiological protection in the revision process, the Commission is expecting a better common understanding and acceptance of its Recommendations.

The membership of the Main Commission during the period of preparation of the present Recommendations was:

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(2001–2005)

R.H. Clarke (Chairman)	A.J. González	Y. Sasaki
R.M. Alexakhin	L.-E. Holm (Vice-Chairman)	C. Streffer
J.D. Boice jr	F.A. Mettler jr	A. Sugier (2003–2005)
R. Cox	Z.Q. Pan	B.C. Winkler (✠ 2003)
G.J. Dicus (✠ 2006)	R.J. Pentreath (2003–2005)	

Scientific Secretary: J. Valentin

(2005–2009)

L.-E. Holm (Chairman)	J.-K. Lee	Y. Sasaki
J.D. Boice jr	H. Menzel (2007–2009)	N. Shandala
C. Cousins	Z.Q. Pan	C. Streffer (2005–2007)
R. Cox (Vice-Chairman)	R.J. Pentreath	A. Sugier
A.J. González	R.J. Preston	

Scientific Secretary: J. Valentin

The work of the Commission was greatly aided by significant contributions from P. Burns, J. Cooper, J.D. Harrison, and W. Weiss. It also benefited from discussions at many international meetings on the present Recommendations.

The Commission wishes to express its appreciation to all international and national organisations, governmental as well as non-governmental, and all individuals who contributed in the development of these Recommendations.

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EXECUTIVE SUMMARY

(a) On 21 March 2007, the Main Commission of the International Commission on Radiological Protection (ICRP) approved these revised Recommendations for a System of Radiological Protection which formally replace the previous Recommendations issued in 1991 as *Publication 60* (ICRP, 1991b) and update the additional guidance on the control of exposure from radiation sources issued since *Publication 60*. These revised Recommendations consolidate and develop the previous Recommendations and guidance.

(b) The Commission has prepared these Recommendations after two phases of international public consultation, one in 2004 and one in 2006, on draft Recommendations. By following this policy of transparency and involvement of stakeholders, the Commission is anticipating a clearer understanding and wider acceptance of its Recommendations.

(c) The major features of the present Recommendations are:

- Updating the radiation and tissue weighting factors in the quantities equivalent and effective dose, and updating the radiation detriment based on the latest available scientific information of the biology and physics of radiation exposure;
- Maintaining the Commission's three fundamental principles of radiological protection, namely justification, optimisation, and the application of dose limits, and clarifying how they apply to radiation sources delivering exposure and to individuals receiving exposure;
- Evolving from the previous process-based protection approach using practices and interventions, by moving to a situation-based approach applying the fundamental principles of justification and optimisation of protection to all controllable exposure situations, which the present Recommendations characterise as planned, emergency, and existing exposure situations;
- Maintaining the Commission's individual dose limits for effective dose and equivalent dose from all regulated sources in planned exposure situations – these limits represent the maximum dose that would be accepted in any planned exposure situations by regulatory authorities;
- Re-enforcing the principle of optimisation of protection, which should be applicable in a similar way to all exposure situations, with restrictions on individual doses and risks, namely dose and risk constraints for planned exposure situations and reference levels for emergency and existing exposure situations; and
- Including an approach for developing a framework to demonstrate radiological protection of the environment.

(d) The Commission's system of radiological protection applies to all exposures to ionising radiation from any source, regardless of its size and origin. However, the Recommendations can apply in their entirety only to situations in which either the source of exposure or the pathways leading to the doses received by individuals can be controlled by some reasonable means. Some exposure situations are excluded from radiological protection legislation, usually on the basis that they are unamenable to control with regulatory instruments, and some exposure situations are

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exempted from some or all radiological protection regulatory requirements where such controls are regarded as unwarranted.

(e) An understanding of the health effects of ionising radiation is central to the Commission's Recommendations. Following a review of the biological and epidemiological information on the health risks attributable to ionising radiation, the Commission has reached the following conclusions. The distribution of risks to different organs/tissues is judged to have changed somewhat since *Publication 60*, particularly in respect of the risks of breast cancer and heritable disease. However, assuming a linear response at low doses, the combined detriment due to excess cancer and heritable effects remains unchanged at around 5% per Sv. Embodied in this current estimate is the use of a dose and dose-rate effectiveness factor for solid cancers which is unchanged at a value of 2. The Commission also judges that, following prenatal exposure, a) cancer risk will be similar to that following irradiation in early childhood and b) threshold dose exists for the induction of malformations and for the expression of severe mental retardation. The Commission has retained the effective dose limits and the equivalent dose limits for the skin, hands/feet, and eye given in *Publication 60* but recognises that further information is needed and revised judgements may be required particularly in respect of the eye. The available data on possible excess in non-cancer diseases (e.g., cardiovascular disorders) are judged to be insufficient to inform on risks at low doses.

(f) The Commission's extensive review of the health effects of ionising radiation has, however, not indicated that any fundamental changes are needed to the system of radiological protection. Importantly, existing numerical recommendations in the policy guidance issued since 1991 remain valid unless otherwise stated. Therefore, these revised Recommendations should not imply any substantial changes to radiological protection regulations that are based on its previous Recommendations and subsequent policy guidance.

(g) The central assumption of a linear dose–response relationship for the induction of cancer and heritable effects, according to which an increment in dose induces a proportional increment in risk even at low doses, continues to provide the basis for the summation of doses from external sources of radiation and from intakes of radionuclides.

(h) The use of equivalent and effective dose remains unchanged, but a number of revisions have been made to the methods used in their calculation. Reviews of the range of available data on the relative biological effectiveness of different radiations, together with biophysical considerations, have led to changes to the values of radiation weighting factors used for neutrons and protons, with values for neutrons given as a continuous function of neutron energy, and the inclusion of a value for charged pions. Radiation weighting factors for photons, electrons, muons, and alpha particles are unchanged.

(i) An important change is that doses from external and internal sources will be calculated using reference computational phantoms of the human body based on medical tomographic images, replacing the use of various mathematical models. For adults, equivalent doses will be calculated by sex-averaging of values obtained using male and female phantoms. Effective dose will then be calculated using revised

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age- and sex-averaged tissue weighting factors, based on updated risk data and intended to apply as rounded values to a population of both sexes and all ages. Effective dose is calculated for a Reference Person and not for an individual.

(j) Effective dose is intended for use as a protection quantity. The main uses of effective dose are the prospective dose assessment for planning and optimisation in radiological protection, and demonstration of compliance with dose limits for regulatory purposes. Effective dose is not recommended for epidemiological evaluations, nor should it be used for detailed specific retrospective investigations of individual exposure and risk.

(k) The collective effective dose quantity is an instrument for optimisation, for comparing radiological technologies and protection procedures, predominantly in the context of occupational exposure. Collective effective dose is not intended as a tool for epidemiological risk assessment, and it is inappropriate to use it in risk projections. The aggregation of very low individual doses over extended time periods is inappropriate, and in particular, the calculation of the number of cancer deaths based on collective effective doses from trivial individual doses should be avoided.

(l) In order to assess radiation doses, models are necessary to simulate the geometry of the external exposure, the biokinetics of incorporated radionuclides, and the human body. The reference models and necessary reference parameter values are established and selected from a range of experimental investigations and human studies through judgements. For regulatory purposes, these models and parameter values are fixed by convention and are not subject to uncertainty. The Commission is aware of uncertainties and lack of precision of the models and parameter values. Efforts are undertaken to critically evaluate and to reduce the uncertainties. For individual retrospective dose and risk assessments, individual parameters and uncertainties have to be taken into account.

(m) The Commission's process of consolidation of previous guidance and recommendations has indicated that some changes to the structure and terminology of the system of protection were desirable in order to improve clarity and utility. In particular the distinction between practices and interventions may not have been clearly understood in the wider radiological protection community. Additionally, there were exposure situations which were difficult to categorise in this manner.

(n) The Commission now recognises three types of exposure situations which replace the previous categorisation into practices and interventions. These three exposure situations are intended to cover the entire range of exposure situations. The three situations are:

- *Planned exposure* situations, which are situations involving the planned introduction and operation of sources. (This type of exposure situation includes situations that were previously categorised as practices.)
- *Emergency exposure* situations, which are unexpected situations such as those that may occur during the operation of a planned situation, or from a malicious act, requiring urgent attention.

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- *Existing exposure* situations, which are exposure situations that already exist when a decision on control has to be taken, such as those caused by natural background radiation.

(o) The three key principles of radiological protection are retained in the revised Recommendations. The principles of *justification* and *optimisation* apply in all three exposure situations whereas the principle of *application of dose limits* applies only for doses expected to be incurred with certainty as a result of planned exposure situations. These principles are defined as follows:

- *The Principle of Justification*: Any decision that alters the radiation exposure situation should do more good than harm.
- *The Principle of Optimisation of Protection*: The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.
- *The Principle of Application of Dose Limits*: The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the Commission.

The Commission continues to distinguish amongst three categories of exposure: occupational exposures, public exposures, and medical exposures of patients (and comforters, carers, and volunteers in research). If a female worker has declared that she is pregnant, additional controls have to be considered in order to attain a level of protection for the embryo/fetus broadly similar to that provided for members of the public.

(p) The revised Recommendations emphasise the key role of the principle of optimisation. This principle should be applied in the same manner in all exposure situations. Restrictions are applied to doses to a nominal individual (the Reference Person), namely dose constraints for planned exposure situations and reference levels for emergency and existing exposure situations. Options resulting in doses greater in magnitude than such restrictions should be rejected at the planning stage. Importantly, these restrictions on doses are applied prospectively, as with optimisation as a whole. If, following the implementation of an optimised protection strategy, it is subsequently shown that the value of the constraint or reference level is exceeded, the reasons should be investigated but this fact alone should not necessarily prompt regulatory action. The Commission expects that this emphasis on a common approach to radiological protection in all exposure situations will aid application of the Commission's Recommendations in the various circumstances of radiation exposure.

(q) The relevant national authorities will often play a major role in selecting values for dose constraints and reference levels. Guidance on the selection process is provided in the revised Recommendations. This guidance takes account of numerical recommendations made previously by the Commission.

(r) Planned exposure situations encompass sources and situations that have been appropriately managed within the Commission's previous Recommendations for

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practices. Protection during the medical uses of radiation is also included in this type of exposure situation. The process of planning protection in planned exposure situations should include consideration of deviations from normal operating procedures including accidents and malicious events. Exposures arising in such circumstances are referred to by the Commission as potential exposures. Potential exposures are not planned but they can be anticipated. The designer and the user of a source must therefore take actions to reduce the likelihood of a potential exposure happening, such as assessing the probability of an event and introducing engineering safeguards commensurate to this probability. Recommendations for planned exposure situations are substantially unchanged from these provided in *Publication 60* and subsequent publications. The dose limits for occupational and public exposures for practices are retained for application to regulated sources in planned exposure situations.

(s) Radiological protection in medicine includes the protection not only of patients but also of individuals exposed to radiation whilst caring for or comforting patients, and volunteers involved in biomedical research. The protection of all of these groups requires special consideration. The Commission's Recommendations for radiological protection and safety in medicine are given in *Publication 73* (ICRP 1996a) which has been further elaborated in a series of publications. The recommendations, guidance and advice in these publications remain valid and are summarised in the present Recommendations and in *Publication 105* (ICRP, 2007b) which was drafted by ICRP Committee 3 to support these Recommendations.

(t) Emphasis on optimisation using reference levels in emergency and existing exposure situations focuses attention on the residual level of dose remaining after implementation of protection strategies. This residual dose should be below the reference level, which represents the total residual dose as a result of an emergency, or in an existing situation, that the regulator would plan not to exceed. These exposure situations often involve multiple exposure pathways which means that protection strategies involving a number of different protective actions will have to be considered. The process of optimisation will however continue to use the dose averted by specific countermeasures as an important input into the development of optimised strategies.

(u) Emergency exposure situations include consideration of emergency preparedness and emergency response. Emergency preparedness should include planning for the implementation of optimised protection strategies which have the purpose of reducing exposures, should the emergency occur, to below the selected value of the reference level. During emergency response, the reference level would act as a benchmark for evaluating the effectiveness of protective actions and as one input into the need for establishing further actions.

(v) Existing exposure situations include naturally occurring exposures as well as exposures from past events and accidents, and practices conducted outside the Commission's Recommendations. In this type of situation, protection strategies will often be implemented in an interactive, progressive manner over a number of years. Indoor radon in dwellings and workplaces is an important existing exposure situation and is one where the Commission made specific recommendations in 1994 in

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Publication 65 (ICRP 1993b). Since then several epidemiological studies have confirmed the health risk from radon exposure and have generally provided support for the Commission's Recommendations on protection against radon. Consistent with its approach to radiological protection in the revised Recommendations, the Commission now recommends that national authorities should set national reference levels as an aid to optimisation of protection against radon exposures. For the sake of continuity and practicability, the Commission retains the upper value of 10 mSv (effective dose, converted by convention from 600 Bq m^{-3} Rn-222 in dwellings) for the annual dose reference level, as given in *Publication 65*. The Commission reaffirms that radon exposure at work at levels above the national reference level should be considered part of occupational exposure whereas exposures at levels below should not. Nevertheless, optimisation is a requirement below the national reference level.

(w) The revised Recommendations acknowledge the importance of protecting the environment. The Commission has previously concerned itself with mankind's environment only with regard to the transfer of radionuclides through it, mainly in the context of planned exposure situations. In such situations, the Commission continues to believe that the standards of environmental control needed to protect the general public would ensure that other species are not placed at risk. To provide a sound framework for environmental protection in all exposure situations, the Commission proposes the use of Reference Animals and Plants. In order to establish a basis for acceptability, additional doses calculated to these reference organisms could be compared with doses known to have specific biological effects and with dose rates normally experienced in the natural environment. The Commission, however, does not propose to set any form of 'dose limits' for environmental protection.

(x) The Commission anticipates that although the revised Recommendations do not contain any fundamental changes to the radiological protection policy, these Recommendations will help to clarify application of the system of protection in the plethora of exposure situations encountered, thereby further improving the already high standards of protection.

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GLOSSARY

α/β ratio

A measure of the curvature of the cell survival curve and a measure of the sensitivity of a tissue or tumour to dose fractionation. The dose at which the linear and quadratic components of cell killing are equal.

Absorbed dose, D

The fundamental dose quantity given by

$$D = \frac{d\bar{\varepsilon}}{dm}$$

where $d\bar{\varepsilon}$ is the mean energy imparted to matter of mass dm by ionising radiation. The SI unit for absorbed dose is joule per kilogram (J kg^{-1}) and its special name is gray (Gy).

Active (red) bone marrow

The organ system bone marrow contains the cell systems for the formation of blood cells starting from the pluripotent haematopietic stem cells to the mature blood cells.

Activity, A

The expectation value of the number of nuclear transformations occurring in a given quantity of material per unit time. The SI unit of activity is per second (s^{-1}) and its special name is becquerel (Bq).

Activity Median Aerodynamic Diameter (AMAD)

The value of aerodynamic diameter such that 50% of the airborne activity in a specified aerosol is associated with particles greater than the AMAD. Used when deposition depends principally on inertial impaction and sedimentation, typically when the AMAD is greater than about 0.5 μm.

Adaptive response

A post-irradiation cellular response which, typically, serves to increase the resistance of the cell to a subsequent radiation exposure.

Ambient dose equivalent, $H^*(10)$

The dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of 10 mm on the radius vector opposing the direction of the aligned field. The unit of ambient dose equivalent is joule per kilogram (J kg^{-1}) and its special name is sievert (Sv).

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Annual intake, *AI*

The amount of a specified radionuclide entering the human body by ingestion or inhalation within one year.

Apoptosis

An active biochemical process of programmed cell death following radiation or other insults.

Averted dose

The dose prevented or avoided by the application of a protective measure or set of protective measures, i.e., the difference between the projected dose if the protective measure(s) had not been applied and the expected residual dose.

Baseline rates

The annual disease incidence observed in a population in the absence of exposure to the agent under study.

Becquerel (Bq)

The special name for the SI unit of activity, 1 Bq = 1 s^{-1} ($\approx$2.7 10^{-11} Ci).

Bioassay

Any procedure used to determine the nature, activity, location, or retention of radionuclides in the body by in vivo measurement or by in vitro analysis of material excreted or otherwise removed from the body.

Biological half-life

The time required, in the absence of further input, for a biological system or compartment to eliminate, by biological processes, half the amount of a substance (e.g., radioactive material) that has entered it.

Brachytherapy

Radiation treatment of a patient using sealed or unsealed sources of radiation placed within the patient's body.

Bystander effect

A response in unirradiated cells that is triggered by signals received from irradiated neighbouring cells.

Categories of exposure

The Commission distinguishes between three categories of radiation exposure: occupational, public, and medical exposures of patients.

Collective dose

See 'Collective effective dose'.

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Collective effective dose, S

The collective effective dose due to individual effective dose values between E_1 and E_2 from a specified source within a specified time period ΔT is defined as:

$$S(E_1, E_2, \Delta T) = \int_{E_1}^{E_2} E \left[\frac{\mathrm{d}N}{\mathrm{d}E}\right]_{\Delta T} \mathrm{d}E$$

It can be approximated as $S = \Sigma_i E_i N_i$ where E_i is the average effective dose for a subgroup i, and N_i is the number of individuals in this subgroup. The time period and number of individuals over which the effective doses are summed should always be specified. The unit of the collective effective dose is joule per kilogram (J kg^{-1}) and its special name is man sievert (man Sv). The number of individuals experiencing an effective dose in the range E_1 to E_2, $N(E_1, E_2, \Delta T)$ is

$$N(E_1, E_2, \Delta T) = \int_{E_1}^{E_2} \left[\frac{\mathrm{d}N}{\mathrm{d}E}\right]_{\Delta T} \mathrm{d}E$$

and the average value of effective dose $\overline{E}(E_1, E_2, \Delta T)$ in the interval of individual doses between E_1 and E_2 for the time period ΔT is:

$$\overline{E}(E_1, E_2, \Delta T) = \frac{1}{N(E_1, E_2, \Delta T)} \int_{E_1}^{E_2} E \left[\frac{\mathrm{d}N}{\mathrm{d}E}\right]_{\Delta T} \mathrm{d}E$$

Committed effective dose, $E(\tau)$

The sum of the products of the committed organ or tissue equivalent doses and the appropriate tissue weighting factors (w_T), where τ is the integration time in years following the intake. The commitment period is taken to be 50 years for adults, and to age 70 years for children.

Committed equivalent dose, $H_T(\tau)$

The time integral of the equivalent dose rate in a particular tissue or organ that will be received by an individual following intake of radioactive material into the body by a Reference Person, where τ is the integration time in years.

Confidence limits

An interval giving the lowest and highest estimate of a parameter that is statistically compatible with the data. For a 95% confidence interval, there is a 95% chance that the interval contains the parameter.

Controlled area

A defined area in which specific protection measures and safety provisions are, or could be, required for controlling normal exposures or preventing the spread of contamination during normal working conditions, and preventing or limiting the extent of potential exposures. A controlled area is often within a supervised area, but need not be.

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DD

See 'Doubling dose'.

Derived air concentration (DAC)

This equals the annual limit on intake, ALI, (of a radionuclide) divided by the volume of air inhaled by a Reference Person in a working year (i.e., 2.2 10^3 m^3). The unit of DAC is Bq m^{-3}.

Designated area

An area that is either 'controlled' or 'supervised'.

Deterministic effect

Injury in populations of cells, characterised by a threshold dose and an increase in the severity of the reaction as the dose is increased further. Also termed tissue reaction. In some cases, deterministic effects are modifiable by post-irradiation procedures including biological response modifiers.

Detriment

The total harm to health experienced by an exposed group and its descendants as a result of the group's exposure to a radiation source. Detriment is a multidimensional concept. Its principal components are the stochastic quantities: probability of attributable fatal cancer, weighted probability of attributable non-fatal cancer, weighted probability of severe heritable effects, and length of life lost if the harm occurs.

Detriment-adjusted risk

The probability of the occurrence of a stochastic effect, modified to allow for the different components of the detriment in order to express the severity of the consequence(s).

Diagnostic reference level

Used in medical imaging with ioning radiation to indicate whether, in routine conditions, the patient dose or administered activity (amount of radioactive material) from a specified procedure is unusually high or low for that procedure.

Directional dose equivalent, $H'(d, \Omega)$

The dose equivalent at a point in a radiation field that would be produced by the corresponding expanded field in the ICRU sphere at a depth, d, on a radius in a specified direction, Ω. The unit of directional dose equivalent is joule per kilogram (J kg^{-1}) and its special name is sievert (Sv).

DMF

Dose modifying factor: the ratio of doses with and without modifying agents, causing the same level of biological effect.

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DNA damage signalling

Interacting biochemical processes which recognise and respond to DNA damage in cells, e.g., by causing the arrest of the reproductive cell cycle.

Differentiation

The process whereby stem cells enter a pathway of proliferation during which daughter cells acquire specialised functions.

Dose and dose-rate effectiveness factor (DDREF)

A judged factor that generalises the usually lower biological effectiveness (per unit of dose) of radiation exposures at low doses and low dose rates as compared with exposures at high doses and high dose rates.

Dose coefficient

Used as a synonym for dose per unit intake of a radioactive substance, but sometimes also used to describe other coefficients linking quantities or concentrations of activity to doses or dose rates, such as the external dose rate at a specified distance above a surface with a deposit of a specified activity per unit area of a specified radionuclide.

Dose commitment, E_c

A calculational tool, defined as the infinite time integral of the per caput dose rate $\dot{E}$ due to a specified event, such as a year of a planned activity causing discharges. In the case of indefinite discharges at a constant rate, the maximum annual per caput dose rate $\dot{E}$ in the future for the specified population will be equal to the dose commitment of one year of practice, irrespective of changes in the population size. If the activity causing discharges is continued only over a time period, τ, the maximum future annual per caput dose will be equal to the corresponding truncated dose commitment, defined as

$$E_c(\tau) = \int_0^{\tau} \dot{E}(t)dt$$

Dose constraint

A prospective and source-related restriction on the individual dose from a source, which provides a basic level of protection for the most highly exposed individuals from a source, and serves as an upper bound on the dose in optimisation of protection for that source. For occupational exposures, the dose constraint is a value of individual dose used to limit the range of options considered in the process of optimisation. For public exposure, the dose constraint is an upper bound on the annual doses that members of the public should receive from the planned operation of any controlled source.

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Dose equivalent, H

The product of D and Q at a point in tissue, where D is the absorbed dose and Q is the quality factor for the specific radiation at this point, thus:

$$H = DQ$$

The unit of dose equivalent is joule per kilogram (J kg^{-1}), and its special name is sievert (Sv).

Dose limit

The value of the effective dose or the equivalent dose to individuals from planned exposure situations that shall not be exceeded.

Dose of record, $H_p(10)$

The effective dose of a worker assessed by the sum of the measured personal dose equivalent $H_p(10)$ and the committed effective dose retrospectively determined for the Reference Person using results of individual monitoring of the worker and ICRP reference biokinetic and dosimetric computational models. Dose of record may be assessed with site-specific parameters of exposure, such as the type of materials and AMAD, but the parameters of the Reference Person shall be fixed as defined by the Commission. Dose of record is assigned to the worker for purposes of recording, reporting and retrospective demonstration of compliance with regulatory dose limits.

Dose-threshold hypothesis

A given dose above background, below which it is hypothesised that the risk of excess cancer and/or heritable disease is zero. (See also Threshold dose for tissue reactions).

Doubling dose (DD)

The dose of radiation (Gy) that is required to produce as many heritable mutations as those arising spontaneously in a generation.

DS02

Dosimetry System 2002, a system for estimating gamma and neutron exposure under a large variety of situations and which allows the calculation of absorbed dose to specific organs for members of the Life Span Study. DS02 improved on the DS86 dose system.

DS86

Dosimetry System 1986, a system for estimating gamma and neutron exposure under a large variety of situations and which then allowed the calculation of absorbed dose to specific organs for members of the Life Span Study.

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Effective dose, E

The tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body, given by the expression:

$$E = \sum_{T} w_T \sum_{R} w_R D_{T,R} \quad \text{or} \quad E = \sum_{T} w_T H_T$$

where H_T or w_R $D_{T,R}$ is the equivalent dose in a tissue or organ, T, and w_T is the tissue weighting factor. The unit for the effective dose is the same as for absorbed dose, J kg^{-1}, and its special name is sievert (Sv).

ELR

See 'Lifetime risk estimates'.

Emergency

A non-routine situation or event that necessitates prompt action primarily to mitigate a hazard or adverse consequences for human health and safety, quality of life, property or the environment. This includes situations for which prompt action is warranted to mitigate the effects of a perceived hazard.

Emergency exposure situation

An unexpected situation that occurs during the operation of a practice, requiring urgent action. Emergency exposure situations may arise from practices.

Employer

An organisation, corporation, partnership, firm, association, trust, estate, public or private institution, group, political or administrative entity, or other persons designated in accordance with national legislation, with recognised responsibility, commitment, and duties towards a worker in her or his employment by virtue of a mutually agreed relationship. A self-employed person is regarded as being both an employer and a worker.

Equivalent dose, H_T

The dose in a tissue or organ T given by:

$$H_T = \sum_{R} w_R D_{T,R}$$

where $D_{T,R}$ is the mean absorbed dose from radiation R in a tissue or organ T, and w_R is the radiation weighting factor. Since w_R is dimensionless, the unit for the equivalent dose is the same as for absorbed dose, J kg^{-1}, and its special name is sievert (Sv).

Excess absolute risk

The rate of disease incidence or mortality in an exposed population minus the corresponding disease rate in an unexposed population. The excess absolute risk is often expressed as the additive excess rate per Gy or per Sv.

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Excess relative risk

The rate of disease in an exposed population divided by the rate of disease in an unexposed population, minus 1.0. This is often expressed as the excess relative risk per Gy or per Sv.

Exclusion

The deliberate exclusion of a particular category of exposure from the scope of an instrument of regulatory control.

Exemption

The determination by a regulatory body that a source or practice activity involving radiation need not be subject to some or all aspects of regulatory control.

Existing exposure situation

A situation that already exists when a decision on control has to be taken, including natural background radiation and residues from past practices that were operated outside the Commission's recommendations.

Exposed individuals

The Commission distinguishes between three categories of exposed individuals: workers (informed individuals), the public (general individuals), and patients, including their comforters and carers.

Fluence (particle fluence), Φ

The quotient of $\mathrm{d}N$ by $\mathrm{d}a$, where $\mathrm{d}N$ is the number of particles incident upon a small sphere of cross-sectional area $\mathrm{d}a$, thus:

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a}$$

FSU

Functional subunits of tissues, e.g., nephrons in kidney, alveoli in lung.

Gray (Gy)

The special name for the SI unit of absorbed dose: 1 Gy = 1 J kg^{-1}.

Growth factors

Molecules that act to control cell reproduction and proliferation/differentiation of a population of cells.

Incidence (incidence rate)

The rate of occurrence of a disease in a population within a specified period of time, often expressed as the number of cases of a disease arising per 100,000 individuals per year (or per 100,000 person-years).

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Induced genomic instability

The induction of an altered cellular state characterised by a persistent increase over many generations in the spontaneous rate of mutation or other genome-related changes.

Intake, I

Activity that enters the body through the respiratory tract or the gastrointestinal tract or the skin.

– Acute intake

A single intake by inhalation or ingestion, taken to occur instantaneously.

– Chronic intake

An intake over a specified period of time.

Justification

The process of determining whether either (1) a planned activity involving radiation is, overall, beneficial, i.e. whether the benefits to individuals and to society from introducing or continuing the activity outweigh the harm (including radiation detriment) resulting from the activity; or (2) a proposed remedial action in an emergency or existing exposure situation is likely, overall, to be beneficial, i.e., whether the benefits to individuals and to society (including the reduction in radiation detriment) from introducing or continuing the remedial action outweigh its cost and any harm or damage it causes.

Kerma, K

The quotient of the sum of the kinetic energies, dE_{tr}, of all charged particles liberated by uncharged particles in a mass dm of material, and the mass dm of that material.

$$K = \frac{dE_{tr}}{dm}$$

Kerma is defined as a non-stochastic quantity and dE_{tr} is the expectation value of the sum of the kinetic energies. The unit for kerma is joule per kilogram (J kg^{-1}) and its special name is gray (Gy).

LAR

See 'Lifetime risk estimates'.

LD50

Dose that is lethal for half of the exposed individuals.

LET

See 'Linear energy transfer'.

Licensee

The holder of a current legal document issued by the regulatory body granting authorisation to perform specified activities related to an installation or activity.

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Life Span Study (LSS)

The long-term cohort study of health effects in the Japanese atomic bomb survivors in Hiroshima and Nagasaki.

Lifetime risk estimates

Several types of lifetime risk estimates can be used to calculate the risk, over a lifetime, that an individual will develop, or die from, a specific disease caused by an exposure: 1) the excess lifetime risk (ELR) which is the difference between the proportion of people who develop or die from the disease in an exposed population and the corresponding proportion in a similar population without the exposure; 2) the risk of exposure-induced death (REID) which is defined as the difference in a cause-specific death rate for exposed and unexposed populations of a given sex and a given age at exposure, as an additional cause of death introduced into a population; 3) loss of life expectancy (LLE) which describes the decrease in life expectancy due to the exposure of interest; and 4) lifetime attributable risk (LAR) which is an approximation of the REID and describes excess deaths (or disease cases) over a follow-up period with population background rates determined by the experience of unexposed individuals. The LAR was used in this report to estimate lifetime risks.

Linear dose response

A statistical model that expresses the risk of an effect (e.g., disease or abnormality) as being proportional to dose.

Linear energy transfer (L or LET)

The average linear rate of energy loss of charged particle radiation in a medium, i.e., the radiation energy lost per unit length of path through a material. That is, the quotient of dE by dl where dE is the mean energy lost by a charged particle owing to collisions with electrons in traversing a distance dl in matter.

$$L = \frac{\mathrm{d}E}{\mathrm{d}l}$$

The unit of L is J m^{-1}, often given in keV μm^{-1}.

Linear-non-threshold (LNT) model

A dose-response model which is based on the assumption that, in the low dose range, radiation doses greater than zero will increase the risk of excess cancer and/or heritable disease in a simple proportionate manner.

Linear-quadratic dose response

A statistical model that expresses the risk of an effect (e.g., disease, death, or abnormality) as the sum of two components, one proportional to dose (linear term) and the other one proportional to the square of dose (quadratic term).

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LLE
See 'Lifetime risk estimates'.

MC
See 'Mutation component'.

Mean absorbed dose in a tissue or organ (T), D_T
The absorbed dose D_T, averaged over the tissue or organ T, which is given by

$$D_T = \frac{\varepsilon_T}{m_T}$$

where ε_T is the mean total energy imparted in a tissue or organ T, and m_T is the mass of that tissue or organ.

Medical exposure
Exposure incurred by patients as part of their own medical or dental diagnosis or treatment; by persons, other than those occupationally exposed, knowingly, while voluntarily helping in the support and comfort of patients; and by volunteers in a programme of biomedical research involving their exposure.

Mendelian diseases
Heritable diseases attributable to single-gene mutations.

Multifactorial diseases
Diseases that are attributable to multiple genetic and environmental factors.

Multistage tumorigenesis
The stepwise acquisition of cellular properties that can lead to the development of tumour from a single (target) cell.

Mutation component (MC)
A quantity that provides a measure of the relative change in disease frequency per unit relative change in mutation rate, i.e., a measure of responsiveness; MC values differ for different classes of heritable disease.

Nominal risk coefficient
Sex-averaged and age-at-exposure-averaged lifetime risk estimates for a representative population.

Non-cancer diseases
Somatic diseases other than cancer, e.g., cardiovascular disease and cataracts.

NORM (naturally occurring radioactive material)
Radioactive material containing no significant amounts of radionuclides other than naturally occurring radionuclides. Material in which the activity

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concentrations of the naturally occurring radionuclides have been changed by some process are included in NORM.

Occupational exposure

This refers to all exposure incurred by workers in the course of their work, with the exception of

1) excluded exposures and exposures from exempt activities involving radiation or exempt sources; 2) any medical exposure; and 3) the normal local natural background radiation.

Operating management

The person or group of persons that directs, controls, and assesses an organisation at the highest level. Many different terms are used, including, e.g., chief executive officer (CEO), director general (DG), managing director (MD), and executive group.

Operational quantities

Quantities used in practical applications for monitoring and investigating situations involving external exposure. They are defined for measurements and assessment of doses in the body. In internal dosimetry, no operational dose quantities have been defined which directly provide an assessment of equivalent or effective dose. Different methods are applied to assess the equivalent or effective dose due to radionuclides in the human body. They are mostly based on various activity measurements and the application of biokinetic models (computational models).

Optimisation of protection (and safety)

The process of determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, as low as reasonably achievable, economic and societal factors being taken into account.

Particle fluence, Φ

See 'Fluence'.

Personal dose equivalent, $H_p(d)$

An operational quantity: the dose equivalent in soft tissue (commonly interpreted as the 'ICRU sphere') at an appropriate depth, d, below a specified point on the human body. The unit of personal dose equivalent is joule per kilogram ($J\ kg^{-1}$) and its special name is sievert (Sv). The specified point is usually given by the position where the individual's dosimeter is worn.

Planned exposure situations

Everyday situations involving the planned operation of sources including decommissioning, disposal of radioactive waste and rehabilitation of the previously occupied land. Practices in operation are planned exposure situations.

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Pooled analysis
An analysis of epidemiological data from several studies based on original data from those studies that are analysed in parallel.

Potential exposure
Exposure that is not expected to be delivered with certainty but that may result from an accident at a source or an event or sequence of events of a probabilistic nature, including equipment failures and operating errors.

PRCF (potential recoverability correction factor)
A set of factors that take account of knowledge that different classes of germ line mutation will show different degrees of recoverability in live-born offspring, i.e., through differing capacities to allow completion of embryonic/fetal development.

Principles of protection
A set of principles that apply equally to all controllable exposure situations: the principle of justification, the principle of optimisation of protection, and the principle of application of limits on maximum doses in planned situations.

Progenitor cell
Undifferentiated cell capable of limited proliferation.

Projected dose
The dose that would be expected to be incurred if no protective measure(s) – were to be taken.

Protection quantities
Dose quantities that the Commission has developed for radiological protection that allow quantification of the extent of exposure of the human body to ionising radiation from both whole and partial body external irradiation and from intakes of radionuclides.

Public exposure
Exposure incurred by members of the public from radiation sources, excluding any occupational or medical exposure and the normal local natural background radiation.

Quality factor, $Q(L)$
The factor characterising the biological effectiveness of a radiation, based on the ionisation density along the tracks of charged particles in tissue. Q is defined as a function of the unrestricted linear energy transfer, L_∞ (often denoted as L or LET), of charged particles in water:

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$$Q(L) = \begin{cases} 1 & L < 10 \text{ keV}/\mu\text{m} \\ 0.32L - 2.2 & 10 \leqslant L \leqslant 100 \text{ keV}/\mu\text{m} \\ 300/\sqrt{L} & L > 100 \text{ keV}/\mu\text{m} \end{cases}$$

Q has been superseded by the radiation weighting factor in the definition of equivalent dose, but it is still used in calculating the operational dose equivalent quantities used in monitoring.

Radiation detriment

A concept used to quantify the harmful health effects of radiation exposure in different parts of the body. It is defined by the Commission as a function of several factors, including incidence of radiation-related cancer or heritable effects, lethality of these conditions, quality of life, and years of life lost owing to these conditions.

Radiation weighting factor, w_R

A dimensionless factor by which the organ or tissue absorbed dose is multiplied to reflect the higher biological effectiveness of high-LET radiations compared with low-LET radiations. It is used to derive the equivalent dose from the absorbed dose averaged over a tissue or organ.

Radioactive material

Material designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity, often taking account of both activity and activity concentration.

Radiological attack

The use of radioactive or nuclear materials for malicious purposes, such as blackmail, murder, sabotage, or terrorism.

Random error

Errors that vary in a non-reproducible way. These errors can be treated statistically by use of the laws of probability.

RBE

See 'Relative biological effectiveness'.

Reference Animals and Plants

A Reference Animal or Plant is a hypothetical entity, with the assumed basic characteristics of a specific type of animal or plant, as described to the generality of the taxonomic level of Family, with defined anatomical, physiological, and life-history properties, that can be used for the purposes of relating exposure to dose, and dose to effects, for that type of living organism.

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Reference Male and Reference Female (Reference Individual)

An idealised male or female with characteristics defined by the Commission for the purpose of radiological protection, and with the anatomical and physiological characteristics defined in the report of the ICRP Task Group on Reference Man (*Publication 89*, ICRP 2002).

Reference Person

An idealised person for whom the organ or tissue equivalent doses are calculated by averaging the corresponding doses of the Reference Male and Reference Female. The equivalent doses of the Reference Person are used for the calculation of the effective dose by multiplying these doses by the corresponding tissue weighting factors.

Reference phantom

Voxel phantoms for the human body (male and female voxel phantoms based on medical imaging data) with the anatomical and physiological characteristics defined in the report of the ICRP Task Group on Reference Man (*Publication 89*, ICRP 2002).

Reference value

The value of a parameter recommended by the Commission for use in a biokinetic model in the absence of more specific information, i.e., the exact value used to calculate the dose coefficients presented in the report. Reference values may be specified to a greater degree of precision than that which would be chosen to reflect the uncertainty with which an experimental value is known, in order to avoid the accumulation of rounding errors in a calculation.

Reference level

In emergency or existing controllable exposure situations, this represents the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented. The chosen value for a reference level will depend upon the prevailing circumstances of the exposure under consideration.

Relative biological effectiveness (RBE)

The ratio of a dose of a low-LET reference radiation to a dose of the radiation considered that gives an identical biological effect. RBE values vary with the dose, dose rate, and biological endpoint considered. In radiological protection, the RBE for stochastic effects at low doses (RBE_M) is of particular interest.

Relative life lost

The ratio of the proportion of observed years of life lost among people dying of a disease in an exposed population and the corresponding proportion in a similar population without the exposure.

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REID

See 'Lifetime risk estimates'.

Relative survival

The ratio of the proportion of cancer patients who survive for a specified number of years (e.g., 5 years) following diagnosis to the corresponding proportion in a comparable set of cancer-free individuals.

Representative Person

An individual receiving a dose that is representative of the more highly exposed individuals in the population (see *Publication 101*, ICRP 2006a). This term is the equivalent of, and replaces, 'average member of the critical group' described in previous ICRP Recommendations.

Residual dose

The dose expected to be incurred after protective measure(s) have beenfully implemented (or a decision has been taken not to implement any protective measures).

Risk constraint

A prospective and source-related restriction on the individual risk (in the sense of probability of detriment due to a potential exposure) from a source, which provides a basic level of protection for the individuals most at risk from a source and serves as an upper bound on the individual risk in optimisation of protection for that source. This risk is a function of the probability of an unintended event causing a dose, and the probability of detriment due to that dose. Risk constraints correspond to dose constraints but refer to potential exposures.

Safety

The achievement of proper operating conditions, prevention of accidents, or mitigation of accident consequences.

Security

The prevention and detection of, and response to, theft, sabotage, unauthorised access, illegal transfer, or other malicious acts involving nuclear material, other radioactive substances, or their associated installations.

Sensitivity analysis

This aims to quantify how the results from a model depend upon the different variables included in it.

Sievert (Sv)

The special name for the SI unit of equivalent dose, effective dose, and operational dose quantities. The unit is joule per kilogram (J kg^{-1}).

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Source

An entity for which radiological protection can be optimised as an integral whole, such as the x-ray equipment in a hospital, or the releases of radioactive materials from an installation. Sources of radiation, such as radiation generators and sealed radioactive materials, and, more generally, the cause of exposure to radiation or to radionuclides.

Source region, S_i

An anatomical region within the reference phantom body which contains the radionuclide following its intake. The region may be an organ, a tissue, the contents of the gastrointestinal tract or urinary bladder, or the surfaces of tissues as in the skeleton, the alimentary tract, and the respiratory tract.

Specific absorbed fraction

The fraction of energy of that emitted as a specified radiation type in a source region, S, that is absorbed in 1 kg of a target tissue, T.

Statistical power

The probability that an epidemiological study will detect a given level of elevated risk with a specified degree of confidence.

Stem cell

Non-differentiated, pluripotent cell, capable of unlimited cell division.

Stochastic effects of radiation

Malignant disease and heritable effects for which the probability of an effect occurring, but not its severity, is regarded as a function of dose without threshold.

Supervised area

A defined area not designated as a controlled area but for which occupational exposure conditions are kept under review, even though no specific protection measures or safety provisions are normally needed.

Systematic error

Errors that are reproducible and tend to bias a result in one direction. Their causes can be assigned, at least in principle, and they can have constant and variable components. Generally these errors cannot be treated statistically.

Target region, T_i

Anatomical region within the body (reference phantom) in which radiation is absorbed. The region may be an organ or a specified tissue as in the gastrointestinal tract, urinary bladder, skeleton, and respiratory tract.

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Threshold dose for tissue reactions
: Dose estimated to result in only 1% incidence of tissue reactions.

Tissue reaction
: See 'Deterministic effect'.

Tissue weighting factor, w_T
: The factor by which the equivalent dose in a tissue or organ T is weighted to represent the relative contribution of that tissue or organ to the total health detriment resulting from uniform irradiation of the body (ICRP 1991b). It is weighted such that:

$$\sum_T w_T = 1$$

Track structure
: Spatial patterns of energy deposition in matter along the track from the passage of ionising radiation.

Transport of risk (also called transfer of risk)
: Taking a risk coefficient estimated for one population and applying it to another population with different characteristics.

Voxel phantom
: Computational anthropomorphic phantom based on medical tomographic images where the anatomy is described by small three-dimensional volume elements (voxels) specifying the density and the atomic composition of the various organs and tissues of the human body.

Worker
: Any person who is employed, whether full time, part time or temporarily, by an employer, and who has recognised rights and duties in relation to occupational radiological protection.

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1. INTRODUCTION

(1) This chapter deals with the history of the Commission and its Recommendations. It sets out the aims and form of this report and indicates why the Commission concerns itself only with protection against ionising radiation.

1.1. The history of the Commission

(2) The International Commission on Radiological Protection, hereafter called the Commission, was established in 1928 by the International Congress of Radiology, with the name of the International X-Ray and Radium Protection Committee (IXRPC), following a decision by the Second International Congress of Radiology. In 1950 it was restructured and renamed as now.

(3) The Commission is an independent charity, i.e., a non-profit-making organisation. The Commission works closely with its sister body, the International Commission on Radiation Units and Measurements (ICRU), and has official relationships with the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the World Health Organization (WHO), and the International Atomic Energy Agency (IAEA). It also has important relationships with the International Labour Organization (ILO), the United Nations Environment Programme (UNEP), and other United Nations bodies. Other organisations with which it works include the Commission of the European Communities ('European Commission', EC), the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA), the International Organization for Standardization (ISO), and the International Electrotechnical Commission (IEC). The Commission also maintains contact with the professional radiological community through its strong links with the International Radiation Protection Association (IRPA). The Commission also takes account of progress reported by national organisations.

1.2. The development of the Commission's Recommendations

(4) The first general Recommendations of the Commission were issued in 1928 and concerned the protection of the medical profession through the restriction of working hours with medical sources (IXRPC, 1928). This restriction is now estimated to correspond to an individual dose of about 1000 millisievert (mSv) per year. The early Recommendations were concerned with avoiding threshold effects, initially in a qualitative manner. A system of measurement of doses was needed before protection could be quantified and dose limits could be defined. In 1934, Recommendations were made implying the concept of a safe threshold about ten times the present annual occupational dose limit (IXRPC, 1934). The tolerance idea continued and, in 1951, the Commission proposed a limit that can now be estimated to be around 3 mSv per week for low-LET radiation (ICRP, 1951). By 1954 the support for a threshold was diminished because of the epidemiological evidence emerging of excess malignant disease amongst American radiologists and the first indication of excess leukaemia in the Japanese A-bomb survivors (ICRP, 1955).

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(5) The development of both the military and industrial uses of nuclear energy led the Commission in the early 1950s to introduce recommendations for the protection of the public. In the Commission's 1956 Recommendations (ICRP, 1957), limits on weekly and accumulated doses were set that corresponded to annual dose limits of 50 mSv for workers and 5 mSv for the public. Recognising the possibility of what are now termed stochastic effects, and the impossibility of demonstrating the existence or non-existence of a threshold for these types of effects, the Commission's 1954 Recommendations advised '*that every effort* [should] *be made to reduce exposures to all types of ionising radiation to the lowest possible level*' (ICRP, 1955). This was successively formulated as the recommendation to maintain exposure 'as low as practicable' (ICRP, 1959), 'as low as readily achievable' (ICRP, 1966), and later on 'as low as reasonably achievable, economic and social considerations being taken into account' (ICRP, 1973).

(6) The Commission's first report in the current series, numbered *Publication 1* (1959), contained the Recommendations approved in 1958. Subsequent general Recommendations have appeared as *Publication 6* (1964), *Publication 9* (1966), *Publication 26* (1977), and *Publication 60* (1991b). These general Recommendations have been supported by many other Publications providing advice on more specialised topics.

(7) In *Publication 26*, the Commission first quantified the risks of stochastic effects of radiation and proposed a System of Dose Limitation (ICRP, 1977) with its three principles of justification, optimisation of protection, and individual dose limitation. In 1990, the Commission largely revised the Recommendations partly because of upward revisions of the estimates of risk from exposure to radiation, and partly to extend its philosophy to a System of Radiological Protection from the system of dose limitation (ICRP, 1991b). The principles of justification, optimisation and individual dose limitation remained, and a distinction between 'practices' and 'interventions' was introduced to take into account the differences in the various types of exposure situations. Moreover, more emphasis was put on the optimisation of protection with constraints so as to limit the inequity that is likely to result from inherent economic and societal judgements.

(8) The annual dose limit of 50 mSv for workers[1] set in 1956, was retained until 1990, when it was further reduced to 20 mSv per year on average based on the revision of the risk for stochastic effects estimated from the life-span study of the Hiroshima–Nagasaki atomic bomb survivors (ICRP, 1991b). The annual dose limit of 5 mSv for members of the public was reduced to 1 mSv per year on average in the Commission's 'Paris statement' (ICRP, 1985b) and in *Publication 60* (ICRP, 1991b) the dose limit was given as 1 mSv in a year with the possibility of averaging over 5 years 'in special circumstances'.

(9) Since *Publication 60*, there has been a series of publications that have provided additional guidance for the control of exposures from radiation sources (see the list of all references). When the 1990 Recommendations are included, these reports

[1] Some terms and units used in older reports have been converted to current terminology for consistency.

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specify some 30 different numerical values for restrictions on individual dose for differing circumstances. Furthermore, these numerical values are justified in many different ways (ICRP, 2006b). In addition the Commission began to develop policy guidance for protection of the environment in *Publication 91* (ICRP, 2003b).

(10) The Commission has now decided to adopt a revised set of Recommendations while at the same time maintaining stability with the previous Recommendations.

(11) The Commission's extensive review of the vast body of literature on the health effects of ionising radiation has not indicated that any fundamental changes are needed to the system of radiological protection. There is, therefore, more continuity than change in these Recommendations; some recommendations are to remain because they work and are clear; others have been updated because understanding has evolved; some items have been added because there has been a void; and some concepts are better explained because more guidance is needed.

(12) The present Recommendations consolidate and add to previous Recommendations issued in various ICRP publications. The existing numerical recommendations in the policy guidance given since 1991 remain valid unless otherwise stated. Thus, these recommendations should not be interpreted as suggesting major changes to radiological protection regulations that are appropriately based on its previous Recommendations in *Publication 60* and subsequent policy guidance. The Recommendations reiterate and strengthen the importance of optimisation in radiological protection and extend the successful experience in the implementation of this requirement for practices (now included in planned exposure situations) to other situations, i.e., emergency and existing exposure situations.

(13) The Commission plans to follow up these Recommendations with reports applying the process of optimisation in different situations.

(14) These consolidated Recommendations are supported by a series of supporting documents, which elaborate on important aspects of the Commission's policy and underpin the Recommendations:

- Low-dose extrapolation of radiation-related cancer risk (*Publication 99*, ICRP, 2005d).
- Biological and epidemiological information on health risks attributable to ionising radiation: A summary of judgements for the purposes of radiological protection of humans (Annex A to these Recommendations).
- Quantities used in radiological protection (Annex B to these Recommendations).
- Optimisation of radiological protection (in *Publication 101*, ICRP, 2006a, Part 2).
- Assessing dose to the Representative Person (in *Publication 101*, ICRP, 2006a, Part 1).
- A framework for assessing the impact of ionising radiation on the environment (*Publication 91*, ICRP, 2003b).
- In addition the Commission is providing guidance on the scope of radiological protection (*Publication 104*, ICRP 2007a), and on radiological protection in medical practice (*Publication 105*, ICRP 2007b).

(15) The principal objective of the Commission has been, and remains, the achievement of the radiological protection of human beings. It has, nevertheless, pre-

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viously regarded the potential impact on other species, although it has not made any general statements about the protection of the environment as a whole. Indeed, in *Publication 60* (ICRP, 1991b) the Commission stated that, at that time, it concerned itself with mankind's environment only with regard to the transfer of radionuclides through the environment, because this directly affects the radiological protection of human beings. The Commission did, however, express the view that the standards of environmental control needed to protect humans to the degree currently thought desirable would ensure that other species are not put at risk.

(16) The Commission continues to believe that this is likely to be the case in general terms under *planned exposure situations* (see Section 5.2 for the definition of planned exposure situations), and that the human habitat has therefore been afforded a fairly high degree of protection. There are, however, other environments to consider, where the Commission's Recommendations for protection of humans have not been used or where humans are absent, and other exposure situations will arise where environmental consequences may need to be taken into account. The Commission is also aware of the needs of some national authorities to demonstrate, directly and explicitly, that the environment is being protected even under planned exposure situations. It therefore now believes that the development of a clearer framework is required in order to assess the relationships between exposure and dose, between dose and effect, and the consequences of such effects for non-human species, on a common scientific basis. This is discussed further in Chapter 8.

(17) The advice of the Commission is aimed principally at regulatory authorities, organisations, and individuals that have responsibility for radiological protection. The Commission's Recommendations have helped in the past to provide a consistent basis for national and regional regulatory standards, and the Commission has been concerned to maintain stability in its Recommendations. The Commission provides guidance on the fundamental principles on which appropriate radiological protection can be based. It does not aim to provide regulatory texts. Nevertheless, it believes that such texts should be developed from, and be broadly consistent with, its guidance.

(18) There is a close connection between the Commission's Recommendations and the International Basic Safety Standards for Protection against Ionizing Radiation and the Safety of Radiation Sources (usually simply called 'the BSS'), which are co-sponsored by the relevant international organisations within the UN family and issued by the IAEA. The governing body of the IAEA has decided that the BSS have to take the Commission's Recommendations into account. The BSS therefore have always followed the establishment of new Recommendations from the Commission; for example, the 1977 and the 1990 ICRP Recommendations were the basis for the revised International Basic Safety Standards published in 1982 and 1996, respectively.

(19) These Recommendations, as in previous reports, are confined to protection against ionising radiation. The Commission recognises the importance of adequate control over sources of non-ionising radiation. The International Commission on Non-Ionizing Radiation Protection, ICNIRP, provides recommendations concerning such sources (ICNIRP, 2004).

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1.2.1. The evolution of dose quantities and their units

(20) The first dose unit, roentgen (r), was established for x rays in 1928 by the International X-ray Unit Committee, which was later to become ICRU (IXRUC, 1928). The first official use of the term 'dose' together with an amended definition of the unit r occurred in the 1937 recommendations of the ICRU (ICRU, 1938). The ICRU suggested the concept of absorbed dose and officially defined the name and its unit 'rad' in 1953 to extend the concept of dose to certain materials other than air (ICRU, 1954).

(21) The first dose quantity incorporating relative biological effectiveness (RBE) of different types of radiation used by the ICRU was the 'RBE dose in rems', which was an RBE-weighted sum of absorbed dose in rads prescribed in the 1956 recommendations of the ICRU. This dose quantity was replaced by the dose equivalent, a result of joint efforts between the ICRU and the Commission, which was defined by the product of absorbed dose, quality factor of the radiation, dose distribution factor and other necessary modifying factors (ICRU, 1962). The 'rem' was retained as the unit of dose equivalent. Furthermore, the ICRU defined another dose quantity, kerma, and changed the name of exposure dose to simple 'exposure' in its 1962 recommendations.

(22) In its 1977 Recommendations (ICRP, 1977), the Commission introduced a new dose equivalent quantity for limitation of stochastic effects by defining a weighted sum of dose equivalents of various tissues and organs of the human body, where the weighting factor was named 'tissue weighting factor' (ICRP, 1977). The Commission named this new weighted dose equivalent quantity 'effective dose equivalent' at the 1978 Stockholm meeting (ICRP, 1978). At the same time, the SI units of dose were adopted, replacing rad by gray (Gy) and rem by sievert (Sv).

(23) In its 1990 Recommendations (ICRP, 1991b), the Commission redefined the body-related dose quantities. For protection purposes, the absorbed dose averaged over a tissue or organ was defined as the basic quantity. In addition, considering that biological effects are not solely governed by the linear energy transfer, the Commission decided to use 'radiation weighting factors', which were selected based on the RBE in inducing stochastic effects at low doses, instead of the quality factors used in calculation of the dose equivalent of the 1977 Recommendations. To distinguish the resulting quantity from the dose equivalent, the Commission named the new quantity 'equivalent dose'. Accordingly, the effective dose equivalent was renamed 'effective dose'. There were some modifications in the tissue weighting factors to take into account the new information on health effects of radiation.

(24) More details of the dosimetric quantities and their units currently in use appear in Chapter 4.

1.3. Structure of the Recommendations

(25) Chapter 2 deals with the aims and the scope of the Recommendations. Chapter 3 deals with biological aspects of radiation, and Chapter 4 discusses the quantities and units used in radiological protection. Chapter 5 describes the conceptual framework of the system of radiological protection and Chapter 6 deals with the implementation of the Commission's Recommendations for the three different types

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of exposure situations. Chapter 7 describes the medical exposure of patients and Chapter 8 discusses protection of the environment.

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2. THE AIMS AND SCOPE OF THE RECOMMENDATIONS

2.1. The aims of the Recommendations

(26) The primary aim of the Commission's Recommendations is to contribute to an appropriate level of protection for people and the environment against the detrimental effects of radiation exposure without unduly limiting the desirable human actions that may be associated with such exposure.

(27) This aim cannot be achieved solely on the basis of scientific knowledge on radiation exposure and its health effects. It requires a model for protecting humans and the environment against radiation. The Recommendations are based on scientific knowledge and on expert judgement. Scientific data, such as those concerning health risks attributable to radiation exposure, are a necessary prerequisite, but societal and economic aspects of protection have also to be considered. All of those concerned with radiological protection have to make value judgements about the relative importance of different kinds of risk and about the balancing of risks and benefits. In this, radiological protection is not different from other fields concerned with the control of hazards. The Commission believes that the basis for, and distinction between, scientific estimations and value judgements should be made clear whenever possible, so as to increase the transparency, and thus the understanding, of how decisions have been reached.

(28) Radiological protection deals with two types of harmful effect. High doses will cause deterministic effects (harmful tissue reactions, see Chapter 3), often of an acute nature, which only appear if the dose exceeds a threshold value. Both high and low doses may cause stochastic effects (cancer or heritable effects), which may be observed as a statistically detectable increase in the incidences of these effects occurring long after exposure.

(29) The Commission's system of radiological protection aims primarily to protect human health. Its health objectives are relatively straightforward: to manage and control exposures to ionising radiation so that deterministic effects are prevented, and the risks of stochastic effects are reduced to the extent reasonably achievable.

(30) In contrast, there is no simple or single universal definition of 'environmental protection' and the concept differs from country to country and from one circumstance to another. Other ways of considering radiation effects are therefore likely to prove to be more useful for non-human species – such as those that cause early mortality, or morbidity, or reduced reproductive success. The Commission's aim is now that of preventing or reducing the frequency of deleterious radiation effects to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities and ecosystems. In achieving this aim, however, the Commission recognises that exposure to radiation is but one factor to consider, and is often likely to be a minor one. The Commission will give guidance and advice to ensure that its approach is commensurate with the level of risk, and compatible with efforts being made to protect the environment from the impacts of other human activities.

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2.2. The basis and structure of the system of protection

(31) Because of the variety of radiation exposure situations and of the need to achieve a consistency across a wide range of applications, the Commission has established a formal system of radiological protection aimed at encouraging a feasible and structured approach to protection. The system has to deal with a number of sources of exposure, some already being in place, and others that may be introduced deliberately as a matter of choice by society or as a result of emergencies. These sources are linked by a variety of interconnected events and situations leading to exposure of individuals, groups, or entire populations, both in the present and in the future. The system of protection has been developed to allow this complex network to be treated by a logical structure.

(32) The system of protection of humans is based on the use of a) reference anatomical and physiological models of the human being for the assessment of radiation doses, b) studies at the molecular and cellular level, c) experimental animal studies, and d) epidemiological studies. The use of models has resulted in the derivation of tabulated, standardised data on the committed 'dose per unit intake' of different radionuclides for internal exposures and 'dose per unit air kerma or fluence' for external exposures of workers, patients, and the public. Epidemiological and experimental studies have resulted in the estimation of risks associated with the external and internal radiation exposure. For biological effects, the data come from human experience supported by experimental biology. For cancer and heritable effects, the Commission's starting points are the results of epidemiological studies and of studies on animal and human genetics. These are supplemented by information from experimental studies on the mechanisms of carcinogenesis and heredity, in order to provide risk estimates at the low doses of interest in radiological protection.

(33) In view of the uncertainties surrounding the values of tissue weighting factors and the estimate of detriment, the Commission considers it appropriate for radiological protection purposes to use age- and sex-averaged tissue weighting factors and numerical risk estimates. The system of protection is sufficiently robust to achieve adequate protection for both sexes. Moreover, this obviates the requirement for sex- and age-specific radiological protection criteria which could prove unnecessarily discriminatory. However, for the purposes of retrospective evaluation of radiation-related risks, such as in epidemiological studies, it is appropriate to use sex- and age-specific data and calculate sex- and age-specific risks. The details of the Commission's methods for calculating detriment are discussed in Annexes A and B.

(34) The Commission's risk estimates are called 'nominal' because they relate to the exposure of a nominal population of females and males with a typical age distribution and are computed by averaging over age groups and both sexes. The dosimetric quantity recommended for radiological protection, effective dose, is also computed by age- and sex-averaging. There are many uncertainties inherent in the definition of nominal factors to assess effective dose. The estimates of fatality and detriment coefficients are adequate for radiological protection purposes, but, as with all estimates derived from epidemiology, the nominal risk coefficients do not apply to

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specific individuals. For the estimation of the likely consequences of an exposure of an individual or a known population, it is necessary to use specific data relating to the exposed individual.

(35) Situations in which the dose thresholds for deterministic effects in relevant organs could be exceeded should be subjected to protective actions under almost any circumstances, as already recommended by the Commission (ICRP, 1999a). It is prudent to take uncertainties in the current estimates of thresholds for deterministic effects into account, particularly in situations involving prolonged exposures. Consequently, annual doses rising towards 100 mSv will almost always justify the introduction of protective actions.

(36) At radiation doses below around 100 mSv in a year, the increase in the incidence of stochastic effects is assumed by the Commission to occur with a small probability and in proportion to the increase in radiation dose over the background dose. Use of this so-called linear-non-threshold (LNT) model is considered by the Commission to be the best practical approach to managing risk from radiation exposure and commensurate with the 'precautionary principle' (UNESCO, 2005). The Commission considers that the LNT model remains a prudent basis for radiological protection at low doses and low dose rates (ICRP, 2005d).

(37) Even within a single class of exposure, an individual may be exposed by several sources, so an assessment of the total exposure has to be attempted. This assessment is called '*individual-related*'. It is also necessary to consider the exposure of all the individuals exposed by a source or group of sources. This procedure is called a '*source-related*' assessment. The Commission emphasises the primary importance of source-related assessments, because action can be taken for a source to assure the protection of individuals from that source.

(38) The probabilistic nature of stochastic effects and the properties of the LNT model make it impossible to derive a clear distinction between 'safe' and 'dangerous', and this creates some difficulties in explaining the control of radiation risks. The major policy implication of the LNT model is that some finite risk, however small, must be assumed and a level of protection established based on what is deemed acceptable. This leads to the Commission's system of protection with its three fundamental principles of protection:

- Justification.
- Optimisation of protection.
- Application of dose limits.

These principles are discussed in more detail in Section 5.6.

(39) In protecting individuals from the harmful effects of ionising radiation, it is the control (in the sense of restriction) of radiation doses that is important, no matter what the source.

(40) The principal components of the system of radiological protection can be summarised as follows.

- A characterisation of the possible situations where radiation exposure may occur (planned, emergency, and existing exposure situations).

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- A classification of the types of exposure (those that are certain to occur and potential exposures, as well as occupational exposure, medical exposure of patients and public exposure).
- An identification of the exposed individuals (workers, patients, and members of the public).
- A categorisation of the types of assessment, namely source-related and individual-related.
- A precise formulation of the principles of protection: justification, optimisation of protection, and application of dose limits.
- A description of the levels of individual doses that require protective action or assessment (dose limits, dose constraints, and reference levels).
- A delineation of the conditions for the safety of radiation sources, including their security and the requirements for emergency preparedness and response.

(41) The implementation of the system of radiological protection as described in these Recommendations and summarised above should be monitored and assessed. Periodic reviews are important with a view to learning from experience and identifying any areas for improvement.

(42) In these Recommendations, the Commission uses the same conceptual approach in the source-related protection, and emphasises the optimisation of protection regardless of the type of source, exposure situation, or exposed individual. Source-related restrictions on doses or risks are applied during the optimisation of protection. In principle, protective options that imply doses above the level of such restrictions should be rejected. The Commission has previously used the term 'constraint' for these restrictions for practices. For reasons of consistency, the Commission will continue to use this term in the context of planned exposure situations because such situations encompass the normal operation of practices. The Commission recognises, however, that the word 'constraint' is interpreted in many languages as a rigorous limit. Such a meaning was never the Commission's intention, as their application must depend upon local circumstances.

(43) Levels for protective action may be selected on the basis of generic considerations including the Commission's general Recommendations (see Table 8, Section 6.5) or best practice. In any specific set of circumstances, particularly in an emergency or an existing exposure situation, it could be the case that no viable protective option can immediately satisfy the level of protection selected from generic considerations. Thus interpreting a constraint rigorously as a form of limit could seriously and adversely distort the outcome of an optimisation process. For this reason, in emergency or existing exposure situations, the Commission proposes to use the term 'reference level' for the restriction on dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented. The Commission wishes to emphasise, however, that the difference in name between planned exposure situations and the other two exposure situations does not imply any fundamental difference in the application of the system of protection. Further guidance on the application of the optimisation

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principle in planned exposure situations, emergency exposure situations, and existing exposure situations is provided in Chapter 6.

2.3. The scope of the Recommendations

(44) The Commission's system of radiological protection applies to all radiation exposures from any source, regardless of its size and origin. The term *radiation* is used to mean ionising radiation. The Commission has been using the term *radiation exposure* (or *exposure* in short) in a generic sense to mean the process of being exposed to radiation or radionuclides, the significance of exposure being determined by the resulting radiation dose (ICRP, 1991b). The term '*source*' is used to indicate the cause of an exposure, and not necessarily a physical source of radiation (see Section 5.1). In general, for the purposes of applying the Recommendations, a source is an entity for which radiological protection can be optimised as an integral whole.

(45) The Commission has aimed to make its Recommendations applicable as widely and as consistently as possible. In particular, the Commission's Recommendations cover exposures to both natural and man-made sources. The Recommendations can apply in their entirety only to situations in which either the source of exposure or the pathways leading to the doses received by individuals can be controlled by some reasonable means. Sources in such situations are called *controllable sources*.

(46) There can be many sources, and some individuals may be exposed to radiation from more than one of them. Provided that doses are below the threshold for deterministic effects (harmful tissue reactions), the presumed proportional relationship between the additional dose attributable to the situation and the corresponding increase in the probability of stochastic effects makes it possible to deal independently with each component of the total exposure and to select those components that are important for radiological protection. Furthermore, it is possible to subdivide these components into groups that are relevant to various purposes.

(47) The Commission has previously distinguished between practices that add doses, and interventions that reduce doses (ICRP, 1991b). The Commission now uses a situation-based approach to characterise the possible situations where radiation exposure may occur as *planned, emergency*, and *existing exposure situations*; it applies one set of fundamental principles of protection to all of these situations (see Section 5.6).

(48) The term '*practice*' has, however, become widely used in radiological protection. The Commission will continue to use this term to denote an activity that causes an increase in exposure to radiation or in the risk of exposure to radiation.

(49) Practices can be activities such as a business, trade, industry or any other productive activity; it can also be a government undertaking, or a charity. It is implicit in the concept of a practice that the radiation sources that it introduces or maintains can be controlled directly by action on the source.

(50) The term '*intervention*' has also become widely used in radiological protection and has been incorporated into national and international standards to describe situations where actions are taken to reduce exposures. The Commission believes

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that it is more appropriate to limit the use of this term to describe protective *actions* that reduce exposure, while the terms 'emergency' or 'existing exposure' will be used to describe radiological *exposure situations* where such protective actions to reduce exposures are required.

2.4. Exclusion and exemption

(51) The fact that the Commission's Recommendations are concerned with any level and type of radiation exposure does not mean that all exposures, all sources, and all human actions, can or need to be equally considered when establishing the legal and regulatory systems for their application. Instead, a graded burden of obligation must be foreseen according to the amenability of a particular source or exposure situation to regulatory controls, and the level of exposure/risk associated with that source or situation.

(52) There are two distinct concepts that delineate the extent of radiological protection control, namely (i) the exclusion of certain exposure situations from radiological protection legislation, usually on the basis that they are not amenable to control with regulatory instruments (cannot be regulated), and (ii) the exemption from some or all radiological protection regulatory requirements for situations where such controls are regarded as unwarranted, often on the basis that the effort to control is judged to be excessive compared to the associated risk (need not be regulated). A legislative system for radiological protection should first establish what should be within the legal system and what should be outside it and therefore excluded from the law and its regulations. Secondly, the system should also establish what could be exempted from some or all regulatory requirements because regulatory action is unwarranted. For this purpose, the legislative framework should permit the regulatory authority to exempt situations from specified regulatory requirements, particularly from those of an administrative nature such as notification and authorisation or exposure assessment and inspection. While exclusion is firmly related to defining the scope of the control system, it may not be sufficient as it is just one mechanism. Exemption, on the other hand, relates to the power of regulatory authorities to determine that a source or practice need not be subject to some or all aspects of regulatory control. The distinction between exclusion and exemption is not absolute; regulatory authorities in different countries may take different decisions about whether to exempt or exclude a specific source or situation.

(53) Exposures that may be excluded from radiological protection legislation include uncontrollable exposures and exposures that are essentially not amenable to control regardless of their magnitude. Uncontrollable exposures are those that cannot be restricted by regulatory action under any conceivable circumstance, such as exposure to the radionuclide potassium–40 incorporated into the human body. Exposures that are not amenable to control are those for which control is obviously impractical, such as exposure to cosmic rays at ground level. The decision as to what exposures are not amenable to control requires a judgment by the legislator, which may be influenced by cultural perceptions. For instance, national attitudes to the reg-

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ulation of exposures to natural occurring radioactive materials are extremely variable.

(54) Further guidance on exclusion and exemption is provided in *Publication 104* (ICRP, 2007a).

2.5. References

ICRP, 1991b. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Ann. ICRP 21 (1–3).

ICRP, 1999a. Protection of the public in situations of prolonged radiation exposure. ICRP Publication 82. Ann. ICRP 29 (1–2).

ICRP, 2005d. Low dose extrapolation of radiation-related cancer risk. ICRP Publication 99. Ann. ICRP 35 (4).

ICRP, 2007a. Scope of radiological protection control measures. ICRP Publication 104. Ann. ICRP 37 (5).

UNESCO, 2005. The Precautionary Principle. United Nations Educational, Scientific and Cultural Organization, Paris, France.

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3. BIOLOGICAL ASPECTS OF RADIOLOGICAL PROTECTION

(55) Most adverse health effects of radiation exposure may be grouped in two general categories:

- deterministic effects (harmful tissue reactions) due in large part to the killing/ malfunction of cells following high doses; and
- stochastic effects, i.e., cancer and heritable effects involving either cancer development in exposed individuals owing to mutation of somatic cells or heritable disease in their offspring owing to mutation of reproductive (germ) cells.

Consideration is also given to effects on the embryo and fetus, and to diseases other than cancer.

(56) In *Publication 60* (ICRP, 1991b) the Commission classified the radiation effects that result in tissue reactions as deterministic effects and used the term stochastic effects for radiation-induced cancer and heritable disease. Effects caused by injury in populations of cells were called non-stochastic in *Publication 41* (ICRP, 1984), and this was replaced by the term deterministic, meaning 'causally determined by preceding events' in *Publication 60* (ICRP, 1991b). The generic terms, deterministic and stochastic effects, are not always familiar to those outside the field of radiological protection. For this and other reasons (given in Annex A), Chapter 3 and Annex A also use the directly descriptive terms tissue reactions and cancer/heritable effects respectively. However, the Commission recognises that the generic terms, deterministic and stochastic effects, have a firmly embedded use in its system of protection and will use the generic and directly descriptive terms synonymously, according to context.

(57) In this respect the Commission notes that some radiation-associated health consequences, particularly some non-cancer effects (see Section 3.3), are not yet sufficiently well understood to assign to either of the generic categories. Since 1990, the Commission has reviewed many aspects of the biological effects of radiation. The views developed by the Commission are summarised in this Chapter with emphasis on effective doses of up to about 100 mSv (or absorbed doses of about 100 mGy of low-LET radiation) delivered as a single dose or accumulated annually. A more detailed summary of the post-1990 developments in radiation biology and epidemiology is provided in Annex A and *Publication 99* (ICRP, 2005d) together with explanations of the judgements that underpin the recommendations made in this Chapter.

3.1. The induction of deterministic effects (harmful tissue reactions)

(58) The induction of tissue reactions is generally characterised by a threshold dose. The reason for the presence of this threshold dose is that radiation damage (serious malfunction or death) of a critical population of cells in a given tissue needs to be sustained before injury is expressed in a clinically relevant form. Above the threshold dose the severity of the injury, including impairment of the capacity for tissue recovery, increases with dose.

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(59) Early (days to weeks) tissue reactions to radiation in cases where the threshold dose has been exceeded may be of the inflammatory type resulting from the release of cellular factors, or they may be reactions resulting from cell loss (*Publication 59*, ICRP, 1991a). Late tissue reactions (months to years) can be of the generic type if they arise as a direct result of damage to that tissue. By contrast other late reactions may be of the consequential type if they arise as a result of early cellular damage (Dörr and Hendry, 2001). Examples of these radiation-induced tissue reactions are given in Annex A.

(60) Reviews of biological and clinical data have led to further development of the Commission's judgements on the cellular and tissue mechanisms that underlie tissue reactions and the dose thresholds that apply to major organs and tissues. However, in the absorbed dose range up to around 100 mGy (low LET or high LET) no tissues are judged to express clinically relevant functional impairment. This judgement applies to both single acute doses and to situations where these low doses are experienced in a protracted form as repeated annual exposures.

(61) Annex A provides updated information on dose thresholds (corresponding to doses that result in about 1% incidence) for various organs and tissues. On the basis of current data the Commission judges that the occupational and public dose limits, including the limits on equivalent dose for the skin, hands/feet and eyes, given in *Publication 60* (ICRP, 1991b) remain applicable for preventing the occurrence of deterministic effects (tissue reactions); see Section 5.10 and Table 6. However, new data on the radiosensitivity of the eye are expected and the Commission will consider these data when they become available. In addition, in Annex A, reference is made to the clinical criteria that apply to dose limits on equivalent doses to the skin.

3.2. The induction of stochastic effects

(62) In the case of cancer, epidemiological and experimental studies provide evidence of radiation risk albeit with uncertainties at doses about 100 mSv or less. In the case of heritable diseases, even though there is no direct evidence of radiation risks to humans, experimental observations argue convincingly that such risks for future generations should be included in the system of protection.

3.2.1. Risk of cancer

(63) The accumulation of cellular and animal data relevant to radiation tumorigenesis has, since 1990, strengthened the view that DNA damage response processes in single cells are of critical importance to the development of cancer after radiation exposure. These data, together with advances in knowledge of the cancer process in general, give increased confidence that detailed information on DNA damage response/repair and the induction of gene/chromosomal mutations can contribute significantly to judgements on the radiation-associated increase in the incidence of cancer at low doses. This knowledge also influences judgements on relative biological

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effectiveness (RBE), radiation weighting factors, and dose and dose-rate effects. Of particular importance are the advances in understanding radiation effects on DNA such as the induction of complex forms of DNA double strand breaks, the problems experienced by cells in correctly repairing these complex forms of DNA damage, and the consequent appearance of gene/chromosomal mutations. Advances in microdosimetric knowledge concerning aspects of radiation-induced DNA damage have also contributed significantly to this understanding (see Annexes A and B).

(64) Although there are recognised exceptions, for the purposes of radiological protection the Commission judges that the weight of evidence on fundamental cellular processes coupled with dose-response data supports the view that, in the low dose range, below about 100 mSv, it is scientifically plausible to assume that the incidence of cancer or heritable effects will rise in direct proportion to an increase in the equivalent dose in the relevant organs and tissues.

(65) Therefore, the practical system of radiological protection recommended by the Commission will continue to be based upon the assumption that at doses below about 100 mSv a given increment in dose will produce a directly proportionate increment in the probability of incurring cancer or heritable effects attributable to radiation. This dose-response model is generally known as 'linear-non-threshold' or LNT. This view accords with that given by UNSCEAR (2000). Other estimates have been provided by various national organisations, some in line with the UNSCEAR view (e.g., NCRP, 2001, NAS/NRC, 2006) while a report from the French Academies (2005) argues in support of a practical threshold for radiation cancer risk. However, from an analysis conducted by the Commission (*Publication 99*, ICRP, 2005d), the Commission considers that the adoption of the LNT model combined with a judged value of a dose and dose rate effectiveness factor (DDREF) provides a prudent basis for the practical purposes of radiological protection, i.e., the management of risks from low-dose radiation exposure.

(66) However, the Commission emphasises that whilst the LNT model remains a scientifically plausible element in its practical system of radiological protection, biological/epidemiological information that would unambiguously verify the hypothesis that underpins the model is unlikely to be forthcoming (see also UNSCEAR, 2000, NCRP 2001). Because of this uncertainty on health effects at low doses, the Commission judges that it is not appropriate, for the purposes of public health planning, to calculate the hypothetical number of cases of cancer or heritable disease that might be associated with very small radiation doses received by large numbers of people over very long periods of time (see also Sections 4.4.7 and 5.8).

(67) In arriving at its practical judgement on the LNT model, the Commission has considered potential challenges associated with information on cellular adaptive responses, the relative abundance of spontaneously arising and low-dose-induced DNA damage and the existence of the post-irradiation cellular phenomena of induced genomic instability and bystander signalling (*Publication 99*, ICRP, 2005d). The Commission recognises that these biological factors, together with possible tumour-promoting effects of protracted irradiation, and immunological phenomena, may influence radiation cancer risk (Streffer et al., 2004), but that current uncertainties

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on the mechanisms and tumorigenic consequences of the above processes are too great for the development of practical judgements. The evidence is reviewed in *Publication 99* and in UNSCEAR (2008). The Commission also notes that since the estimation of nominal cancer risk coefficients is based upon direct human epidemiological data, any contribution from these biological mechanisms would be included in that estimate. Uncertainty with regard to the role of these processes in cancer risk will remain until their relevance to cancer development in vivo is demonstrated and there is knowledge of the dose dependence of the cellular mechanisms involved.

(68) Since 1990, further epidemiological information has accumulated on the risk of organ-specific cancer following exposure to radiation. Much of this new information has come from the continuing follow-up of survivors of the atomic bomb explosions in Japan in 1945 – the Life Span Study (LSS). For cancer mortality (Preston et al., 2003) the follow-up is 47 years (October 1950–December 1997); for cancer incidence (Preston et al., 2007) the follow-up period is 41 years (January 1958 to December 1998). These latter data, which were not available in 1990, can provide more reliable estimates of risk principally because cancer incidence can allow for more accurate diagnosis. The Commission has therefore placed emphasis on incidence data for its present Recommendations. In addition, epidemiological data from the LSS provide further information on the temporal and age-dependent pattern of radiation cancer risk, particularly the assessment of risk amongst those exposed at early ages. Overall, current cancer risk estimates derived from the LSS are not greatly changed since 1990, but the inclusion of the cancer incidence data provides a firmer foundation for the risk modelling described in Annex A.

(69) The LSS is not, however, the sole source of information on radiation cancer risk and the Commission has considered data from medical, occupational, and environmental studies (UNSCEAR, 2000, NAS/NRC, 2006). For cancers at some sites there is reasonable compatibility between the data from the LSS and those from other sources. However, the Commission recognises that, for a number of organ/tissue risks and for overall risks, there are differences in radiation risk estimates among the various data sets. Most studies on environmental radiation exposures currently lack sufficient data on dosimetry and tumour ascertainment to contribute directly to risk estimation by the Commission but may be a potentially valuable data source in the future.

(70) A dose and dose-rate effectiveness factor (DDREF) has been used by UNSCEAR to project cancer risk determined at high doses and high dose rates to the risks that would apply at low doses and low dose rates. In general, cancer risk at these low doses and low dose rates is judged, from a combination of epidemiological, animal, and cellular data, to be reduced by the value of the factor ascribed to DDREF. In its 1990 Recommendations the Commission made the broad judgement that a DDREF of 2 should be applied for the general purposes of radiological protection.

(71) In principle, epidemiological data on protracted exposure, such as those from environmental and occupational circumstances, should be directly informative on judgements of DDREF. However, the statistical precision afforded by these studies

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Table 1. Detriment-adjusted nominal risk coefficients (10^{-2} Sv^{-1}) for stochastic effects after exposure to radiation at low dose rate.

Exposed population	Cancer		Heritable effects		Total	
	Present[1]	*Publ. 60*	Present[1]	*Publ. 60*	Present[1]	*Publ. 60*
Whole	5.5	6.0	0.2	1.3	5.7	7.3
Adult	4.1	4.8	0.1	0.8	4.2	5.6

[1] Values from Annex A.

and other uncertainties associated with the inability to adequately control for confounding factors (see Annex A), do not allow for a precise estimate of DDREF at this time. Accordingly the Commission has decided to continue to use broad judgements in its choice of DDREF based upon dose-response features of experimental data, the LSS, and the results of probabilistic uncertainty analysis conducted by others (NCRP, 1997, EPA, 1999, NCI/CDC, 2003, Annex A).

(72) The BEIR VII Committee (NAS/NRC, 2006) recently combined radiobiological and epidemiological evidence concerning DDREF via a Bayesian statistical analysis. The data sets used were: a) solid cancer in the LSS; and b) cancer and life shortening in animals. The modal value of DDREF from these analyses was 1.5 with a range of 1.1 to 2.3 and from this the BEIR VII Committee chose a value of 1.5. The BEIR VII Committee recognised the subjective and probabilistic uncertainties inherent in their specific choice, and a DDREF of 2 remains compatible with the data used and analyses conducted. Further to this, the Commission notes from Annex A that, for the induction of gene and chromosomal mutations, values of DDREF generally fall in the range of 2–4, and for the induction of cancer in animals and life shortening in animals, values of DDREF generally fall in the range of 2–3.

(73) In considering all the data noted above, and recognising the broad range of experimental animal data showing reduction in carcinogenic effectiveness and life-shortening following protracted exposures, the Commission finds no compelling reason to change its 1990 recommendations of a DDREF of 2. However, the Commission emphasises that this continues to be a broad whole number judgement for the practical purposes of radiological protection which embodies elements of uncertainty. This risk reduction factor of 2 is used by the Commission to derive the nominal risk coefficients for all cancers given in Table 1, but the Commission recognises that, in reality, different dose and dose rate effects may well apply to different organs/tissues.

3.2.2. Risk of heritable effects

(74) There continues to be no direct evidence that exposure of parents to radiation leads to excess heritable disease in offspring. However, the Commission judges that there is compelling evidence that radiation causes heritable effects in experimental animals. Therefore, the Commission prudently continues to include the risk of heritable effects in its system of radiological protection.

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(75) The Commission also notes reports (reviewed in UNSCEAR, 2001) which argue, on the basis of A-bomb survivor and mouse genetic data, that the risk of heritable diseases tended to be overestimated in the past. There are some post-1990 human and animal data on the quantitative aspects of radiation-induced germ cell mutation that impact on the Commission's judgement on the risk of induction of genetic disease expressing in future generations. There have also been substantial advances in the fundamental understanding of human genetic diseases and the process of germ line mutagenesis including that occurring after radiation. The Commission has reappraised the methodology used in *Publication 60* for the estimation of heritable risks including risks of multifactorial diseases (*Publication 83*, ICRP, 1999b).

(76) The Commission has now adopted a new framework for the estimation of heritable risks that employs data from human and mouse studies (UNSCEAR, 2001, NAS/NRC, 2006). Also, for the first time, a scientifically justified method for the estimation of risk of multifactorial disease has been included. Mouse studies continue to be used to estimate genetic risks because of the lack of clear evidence in humans that germline mutations caused by radiation result in demonstrable genetic effects in offspring.

(77) The new approach to heritable risks continues to be based on the concept of the doubling dose (DD) for disease-associated mutations used in *Publication 60*. However, the methodology differs in that recoverability of mutations in live births is allowed for in the estimation of DD. An additional difference is that direct data on spontaneous human mutation rates are used in conjunction with radiation-induced mutation rates derived from mouse studies. This new methodology (see Annex A, Box A.2) is based on the UNSCEAR 2001 report and has also been used recently by NAS/NRC (2006). In *Publication 60* genetic risks were expressed at a theoretical equilibrium between mutation and selection. In the light of further knowledge the Commission judges that many of the underlying assumptions in such calculations are no longer sustainable. The same view has been expressed by UNSCEAR (2001) and NAS/NRC (2006). Accordingly, the Commission now expresses genetic risks up to the second generation only.

(78) The Commission judges that this procedure will not lead to a significant underestimation of heritable effects. This issue is discussed in UNSCEAR (2001) and in detail in Annex A where it is argued that there are no substantial differences between genetic risks expressed at 2 and 10 generations.

(79) The Commission's present estimate of genetic risks up to the second generation of about 0.2% per Gy is essentially the same as that cited by UNSCEAR (2001) (see Annex A and UNSCEAR 2001, Table 46). However, given the major changes in methodology, the close similarity of the present second generation risk to that of *Publication 60* is coincidental. The present value relates to continuous low-dose-rate exposures over these two generations.

3.2.3. Detriment-adjusted nominal risk coefficients for cancer and heritable effects

(80) New information on the risks of radiation-induced cancer and heritable effects has been used in risk modelling and disease detriment calculations in order to estimate sex-averaged nominal risk coefficients.

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(81) It remains the policy of the Commission that its recommended nominal risk coefficients should be applied to whole populations and not to individuals. The Commission believes that this policy provides for a general system of protection that is simple and sufficiently robust. In retaining this policy the Commission does however recognise that there are significant differences in risk between males and females (particularly for the breast) and in respect of age at exposure. Annex A provides data and calculations relating to these differences.

(82) The calculation of sex-averaged nominal risk coefficients for cancer involves the estimation of nominal risks for different organs and tissues, adjustment of these risks for DDREF, lethality, and quality of life and, finally, the derivation of a set of site-specific values of relative detriment, which includes heritable effects from gonadal exposures. These relative detriments provide the basis of the Commission's system of tissue weighting which is explained in Annex A (Box A.1) and summarised in Chapter 4.

(83) On the basis of these calculations the Commission proposes nominal probability coefficients for detriment-adjusted cancer risk as 5.5 10^{-2} Sv^{-1} for the whole population and 4.1 10^{-2} Sv^{-1} for adult workers. For heritable effects, the detriment-adjusted nominal risk in the whole population is estimated as 0.2 10^{-2} Sv^{-1} and in adult workers as 0.1 10^{-2} Sv^{-1}. The most significant change from *Publication 60* is the 6–8 fold reduction in the nominal risk coefficient for heritable effects. These estimates are shown in Table 1, where they are compared with the estimates of detriment used in the 1990 Recommendations in *Publication 60* (ICRP, 1991b). The revised estimate of genetic risk has reduced the judged value of the tissue weighting factor for the gonads considerably (see Chapter 4 and detailed arguments in Annex A). However, the Commission emphasises that this reduction in the gonadal tissue weighting factor provides no justification for allowing controllable gonadal exposures to increase in magnitude.

(84) The present nominal probability coefficients for cancer shown in Table 1 have been computed in a different manner from that of *Publication 60*. The present estimate is based upon data on cancer incidence weighted for lethality and life impairment, whereas in *Publication 60* detriment was based upon fatal cancer risk weighted for non-fatal cancer, relative life lost for fatal cancers and life impairment for non-fatal cancer.

(85) Note that, although all coefficients in Table 1 are presented as fractional values, this presentation is used for the purposes of comparability to Annex A only and does not imply a level of precision (see paragraphs 81 and 82).

(86) In spite of changes in the cancer risk data and their treatment, the present nominal risk coefficients are wholly compatible with those presented by the Commission in *Publication 60* (ICRP, 1991b). Given the uncertainties discussed in Annex A, the Commission considers that the small difference in the estimate of nominal risk since 1990 is of no practical significance.

(87) It is therefore the recommendation of the Commission that the approximated overall fatal risk coefficient of 5% per Sv on which current international radiation safety standards are based continues to be appropriate for the purposes of radiological protection.

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3.2.4. Genetic susceptibility to cancer

(88) The issue of individual genetic differences in susceptibility to radiation-induced cancer was noted in *Publication 60* and reviewed in *Publication 79* (ICRP, 1998a). Since 1990, there has been a remarkable expansion in knowledge of the various single gene human genetic disorders, where excess spontaneous cancer is expressed in a high proportion of gene carriers – the so-called high penetrance genes which can be strongly expressed as excess cancer. Studies with cultured human cells and genetically altered laboratory rodents have also contributed much to knowledge and, with more limited epidemiological and clinical data, suggest that most of the rare single gene, cancer prone disorders will show greater-than-normal sensitivity to the tumorigenic effects of radiation.

(89) There is also a growing recognition, with some limited supporting data, that variant genes of lower penetrance through gene-gene and gene-environment interactions can result in a highly variable expression of cancer following radiation exposure.

(90) On the basis of the data and judgements developed in *Publication 79* and further information reviewed in the UNSCEAR (2000, 2001) and NAS/NRC (2006) reports, the Commission believes that strongly expressing, high penetrance, cancer genes are too rare to cause significant distortion of population-based estimates of low-dose radiation cancer risk. Although the Commission recognises that variant cancer genes of low penetrance may, in principle, be sufficiently common to impact upon population-based estimates of radiation cancer risk, the information available is insufficient to provide a meaningful quantitative judgement on this issue.

3.3. The induction of diseases other than cancer

(91) Since 1990 evidence has accumulated that the frequency of non-cancer diseases is increased in some irradiated populations. The strongest statistical evidence for the induction of these non-cancer effects at effective doses of the order of 1 Sv derives from the most recent mortality analysis of the Japanese atomic bomb survivors followed after 1968 (Preston et al., 2003). That study has strengthened the statistical evidence for an association with dose – particularly for heart disease, stroke, digestive disorders, and respiratory disease. However, the Commission notes current uncertainties on the shape of the dose-response at low doses and that the LSS data are consistent both with there being no dose threshold for risks of disease mortality and with there being a dose threshold of around 0.5 Sv. Additional evidence of the non-cancer effects of radiation, albeit at high doses, comes from studies of cancer patients receiving radiotherapy but these data do not clarify the issue of a possible dose threshold (Annex A). It is also unclear what forms of cellular and tissue mechanisms might underlie such a diverse set of non-cancer disorders.

(92) Whilst recognising the potential importance of the observations on non-cancer diseases, the Commission judges that the data available do not allow for their inclusion in the estimation of detriment following low radiation doses, less than

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about 100 mSv. This agrees with the conclusion of UNSCEAR (2008), which found little evidence of any excess risk below 1 Gy.

3.4. Radiation effects in the embryo and fetus

(93) The risks of tissue reactions and malformation in the irradiated embryo and fetus have been reviewed in *Publication 90* (ICRP 2003a). In the main, this review reinforced the judgements on in-utero risks given in *Publication 60* although on some issues new data allow for clarification of views. On the basis of *Publication 90*, the Commission has reached the following conclusions on the in-utero risks of tissue injury and malformation at doses below about 100 mGy of low-LET radiation.

(94) The new data confirm embryonic susceptibility to the lethal effects of irradiation in the pre-implantation period of embryonic developments. At doses under 100 mGy, such lethal effects will be very infrequent.

(95) In respect of the induction of malformations, the new data strengthen the view that there are gestational age-dependent patterns of in-utero radiosensitivity with maximum sensitivity being expressed during the period of major organogenesis. On the basis of animal data it is judged that there is a true dose threshold of around 100 mGy for the induction of malformations; therefore, for practical purposes, the Commission judges that risks of malformation after in-utero exposure to doses well below 100 mGy are not expected.

(96) The *Publication 90* (ICRP, 2003a) review of A-bomb survivor data on the induction of severe mental retardation after irradiation in the most sensitive prenatal period (8–15 weeks post conception) supports a dose threshold of at least 300 mGy for this effect and therefore the absence of risk at low doses. The associated data on IQ losses estimated at around 25 points per Gy are more difficult to interpret and the possibility of a non-threshold dose response cannot be excluded. However, even in the absence of a true dose threshold, any effects on IQ following in-utero doses under 100 mGy would be of no practical significance. This judgement accords with that developed in *Publication 60* (ICRP, 1991b).

(97) *Publication 90* also reviewed data concerning cancer risk following in-utero irradiation. The largest case-control studies of in-utero medical irradiation provided evidence of increased childhood cancer of all types. The Commission recognises that there are particular uncertainties on the risk of radiation-induced solid cancers following in-utero exposure. The Commission considers that it is prudent to assume that life-time cancer risk following in-utero exposure will be similar to that following irradiation in early childhood, i.e., at most, about three times that of the population as a whole.

3.5. Judgements and uncertainties

(98) Although the potential importance of synergistic effects between radiation and other agents is recognised by the Commission, at the present time there is no firm evidence for such interactions at low doses that would justify a modification of existing radiation risk estimates (UNSCEAR, 2000).

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(99) Taking into account the information discussed in this Section, the practical system of radiological protection recommended by the Commission will continue to be based upon the assumption that, at doses below about 100 mSv, a given increment in dose will produce a directly proportionate increment in the probability of incurring cancer or heritable effects attributable to radiation. The Commission considers that the continued application of the LNT model combined with a judged value of DDREF provides a prudent basis for practical purposes of radiological protection, i.e., the management of risks from low-dose radiation exposure in prospective situations.

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4. QUANTITIES USED IN RADIOLOGICAL PROTECTION

4.1. Introduction

(100) Special *dosimetric quantities* have been developed for the assessment of doses from radiation exposures. The fundamental *protection quantities* adopted by the Commission are based on measures of the energy deposited in organs and tissues of the human body. In order to relate the radiation dose to radiation risk (detriment), it is also necessary to take into account variations in the biological effectiveness of radiations of different quality as well as the varying sensitivity of organs and tissues to ionising radiation.

(101) In *Publication 26* (ICRP, 1977) the protection quantities *dose equivalent*, for organs and tissues of the human body, and *effective dose equivalent* were introduced. The definition and method of calculation of these quantities were modified in *Publication 60* (ICRP, 1991b) to give the quantities *equivalent dose* and *effective dose*. The development of the quantities effective dose equivalent and effective dose has made a significant contribution to radiological protection as it has enabled doses to be summed from whole and partial body exposure from external radiation of various types and from intakes of radionuclides.

(102) Equivalent dose and effective dose cannot be measured directly in body tissues. The protection system therefore includes *operational quantities* that can be measured and from which the equivalent dose and the effective dose can be assessed.

(103) The general acceptance of effective dose and the demonstration of its utility in radiological protection are important reasons for maintaining it as the central quantity for dose assessments in radiological protection. There are, however, a number of aspects of the dosimetry system given in *Publication 60* that need to be addressed and clarified as summarised below and given in more detail in Annex B. Care is also needed in describing the situations in which effective dose should and should not be used. In some situations, tissue absorbed dose or equivalent dose are more appropriate quantities.

4.2. Considerations of health effects

(104) Radiological protection in the low dose range is primarily concerned with protection against radiation-induced cancer and heritable disease. These effects are taken to be probabilistic in nature, with no threshold, and to increase in frequency in proportion to the radiation dose (see Chapter 3 and Annex A). In the definition and calculation of effective dose the recommended radiation weighting factors, w_R, allow for the differences in the effect of various radiations in causing stochastic effects while tissue weighting factors, w_T, allow for the variations in radiation sensitivity of different organs and tissues to the induction of stochastic effects (see Section 4.3.4 and Annex B). The radiation weighting factors for radiations characterised by a high linear energy transfer, so-called high-LET radiations (see Section 4.3.3), are derived for stochastic effects at low doses.

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(105) At high doses, and especially in emergency situations, radiation exposures may cause deterministic effects (tissue reactions). Such clinically observable damage occurs above threshold doses. The extent of damage depends upon the absorbed dose and dose rate as well as radiation quality (see Annexes A and B) and the sensitivity of the tissue. In general, values of relative biological effectiveness (RBE) for tissue reactions caused by high-LET radiations are found to be lower than those obtained for stochastic effects at low doses, and the relative sensitivity of tissues also differs. The quantities equivalent dose and effective dose should not be used to quantify higher radiation doses or to make decisions on the need for any treatment related to tissue reactions. For such purposes, doses should be evaluated in terms of absorbed dose (in gray, Gy), and where high-LET radiations (e.g., neutrons or alpha particles) are involved, an absorbed dose, weighted with an appropriate RBE, should be used (see Annex B).

4.3. Dose quantities

(106) The procedure for the assessment of effective dose adopted by the Commission is to use *absorbed dose* as the fundamental physical quantity, to average it over specified organs and tissues, to apply suitably chosen weighting factors to take account of differences in biological effectiveness of different radiations to give the quantity equivalent dose, and to consider differences in sensitivities of organs and tissues to stochastic health effects. Values of the equivalent dose to organs and tissues weighted for the radiosensitivity of these organs and tissues are then summed to give the effective dose. This quantity is based on the exposure to radiation from external radiation fields and from incorporated radionuclides as well as on the primary physical interactions in human tissues and on judgements about the biological reactions resulting in stochastic health effects (Annex B).

4.3.1. Absorbed dose

(107) In radiation biology, clinical radiology, and radiological protection the absorbed dose, D, is the basic physical dose quantity, and it is used for all types of ionising radiation and any irradiation geometry. It is defined as the quotient of $\mathrm{d}\bar{\varepsilon}$ by $\mathrm{d}m$, where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted to matter of mass $\mathrm{d}m$ by ionising radiation, that is

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m} \tag{4.1}$$

(108) The SI unit of absorbed dose is J kg^{-1} and its special name is gray (Gy). Absorbed dose is derived from the mean value of the stochastic quantity of energy imparted, ε, and does not reflect the random fluctuations of the interaction events in tissue. While it is defined at any point in matter, its value is obtained as an average over a mass element $\mathrm{d}m$ and hence over many atoms or molecules of matter. Absorbed dose is a measurable quantity and primary standards exist to determine its value.

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The definition of absorbed dose has the scientific rigour required for a basic physical quantity (Annex B).

4.3.2. Averaging of dose

(109) When using the quantity absorbed dose in practical protection applications, doses are averaged over tissue volumes. It is assumed that, for low doses, the mean value of absorbed dose averaged over a specific organ or tissue can be correlated with radiation detriment for stochastic effects in that tissue with an accuracy sufficient for the purposes of radiological protection. The averaging of absorbed doses in tissues or organs and the summing of weighted mean doses in different organs and tissues of the human body comprise the basis for the definition of the protection quantities which are used for limiting stochastic effects at low doses. This approach is based on the LNT model and therefore allows the addition of doses resulting from external and internal exposure.

(110) The averaging of absorbed dose is carried out over the mass of a specified organ (e.g., liver) or tissue (e.g., muscle) or the sensitive region of a tissue (e.g., endosteal surfaces of the skeleton). The extent to which the mean dose value is representative of the absorbed dose in all regions of the organs, tissues or tissue regions depends, for external irradiation, on the homogeneity of the exposure and on the range of the radiation incident on the body. The homogeneity of the dose distribution in the low dose range depends also upon microdosimetric properties. For radiations with low penetration or limited range (e.g., low-energy photons or charged particles) as well as for widely distributed tissues and organs (e.g., red bone marrow, lymphatic nodes, or skin) the absorbed dose distribution within the specified organ or tissue will be even more heterogeneous. In cases of extreme partial body exposure, tissue damage may occur even if the mean organ or tissue dose or the effective dose is below the dose limit. A special limit on local skin dose, for example, takes account of this situation in the case of exposure by low-penetrating radiation.

(111) The absorbed dose distribution in organs from radiations emitted by radionuclides retained within body organs or tissues, so-called internal emitters, depends on the penetration and range of the emitted radiations. Thus, the absorbed dose distribution for radionuclides emitting alpha particles, soft beta particles, low-energy photons, or Auger electrons may be highly heterogeneous (see Annex B). This heterogeneity applies in particular to radionuclides in the respiratory and alimentary systems, and the skeleton. Specific dosimetric models have been developed to take account of such heterogeneity in the distribution and retention of activity and of sensitive regions in these particular cases.

4.3.3. Equivalent dose and radiation weighting factors

(112) The protection quantities are used to specify exposure limits to ensure that the occurrence of stochastic health effects is kept below unacceptable levels and that tissue reactions are avoided. The definition of the protection quantities is based on

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Table 2. Recommended radiation weighting factors.

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons[a] and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (see Fig. 1 and Eq. 4.3)

All values relate to the radiation incident on the body or, for internal radiation sources, emitted from the incorporated radionuclide(s).

[a] Note the special issue of Auger electrons discussed in paragraph 116 and in Section B.3.3 of Annex B.

the average absorbed dose, $D_{T,R}$ in the volume of a specified organ or tissue T (see Table 3), due to radiation of type R (see Table 2). The radiation R is given by the type and energy of radiation either incident on the body or emitted by radionuclides residing within it. The protection quantity *equivalent dose* in an organ or tissue, H_T, is then defined by

$$H_T = \sum_R w_R D_{T,R} \tag{4.2}$$

where w_R is the radiation weighting factor for radiation R. The sum is performed over all types of radiations involved. The unit of equivalent dose is J kg^{-1} and has the special name sievert (Sv).

(113) In the early 1960s, radiation weighting in the definition of radiological protection quantities was related to the radiation quality factor, Q, as a function of LET and denoted as L in the $Q(L)$ function of *Publication 26* (ICRP, 1977). In *Publication 60* (ICRP, 1991b) the method of radiation weighting was changed in the calculation of the protection quantities equivalent dose and effective dose. The Commission selected a general set of radiation weighting factors (w_R) that were considered to be appropriate for application in radiological protection. The values of w_R were defined largely on the basis of the relative biological effectiveness (RBE) of the different radiations.

(114) A revised set of w_R values has been adopted in these Recommendations based upon a re-evaluation of the available data (see Annexes A and B). The values of w_R for neutrons and protons given in these Recommendations differ from those given in *Publication 60* (see below and Annex B). A w_R value for charged pions has been included. The value of w_R for photons is the same for x rays and gamma rays of all energies. The numerical values of w_R are specified in terms of type and, in the case of neutrons, in terms of energy of radiation either incident on the human body or emitted by radionuclides residing in the body (Table 2). The values of w_R are

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Table 3. Recommended tissue weighting factors.

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
	Total	1.00

* Remainder tissues: Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate (♂), Small intestine, Spleen, Thymus, Uterus/cervix (♀).

selected by judgement on the basis of a broad range of experimental RBE data which are relevant to stochastic effects. The RBE values increase to a maximum (RBE_M) with decreasing radiation dose (ICRP, 2003c). Values of RBE_M have been used for w_R selection, and fixed values are assigned to these w_R factors for radiological protection purposes.

(115) ***Reference radiation.*** Values of RBE obtained experimentally depend on the reference radiation chosen. Generally, low-LET photon radiation is taken as the reference, although no specific energy has been agreed upon for this purpose. When radiation weighting factors were selected for *Publication 60*, a broad range of experimental RBE data using either high energy x rays above about 200 kV or cobalt–60 or caesium–137 gamma radiation was considered (see Annex B). This approach is also used in these Recommendations, although it should be recognised that experimentally different RBE values can result depending upon the choice of the reference radiation between x rays and higher energy gamma radiation (e.g., cobalt–60). Such differences have been established mainly in studies on cells in vitro (see Annex B).

(116) ***Photons, electrons, and muons.*** Photons, electrons, and muons are radiations with LET values of less than 10 keV/μm. These radiations have always been given a radiation weighting of 1. There are good arguments (see Annex B) to continue to use a w_R of 1 for all low-LET radiations (Annex B, Table 3). This does not, however, imply that there are no differences in radiation quality of photons of different energies. The proposed simplification is sufficient only for the intended application of equivalent dose and effective dose, e.g., for dose limitation and assessment and control of doses in the low-dose range. In cases where individual retrospective risk assessments have to be made, more detailed information on the radiation field and appropriate RBE values may need to be considered if relevant data are available. Heterogeneity of the radiation dose within cells, as can occur with tritium or Auger emitters incorporated into DNA, may also require specific analysis (see Annex B). Equivalent dose and effective dose are not appropriate quantities for use in such assessments (see Section 4.4.6).

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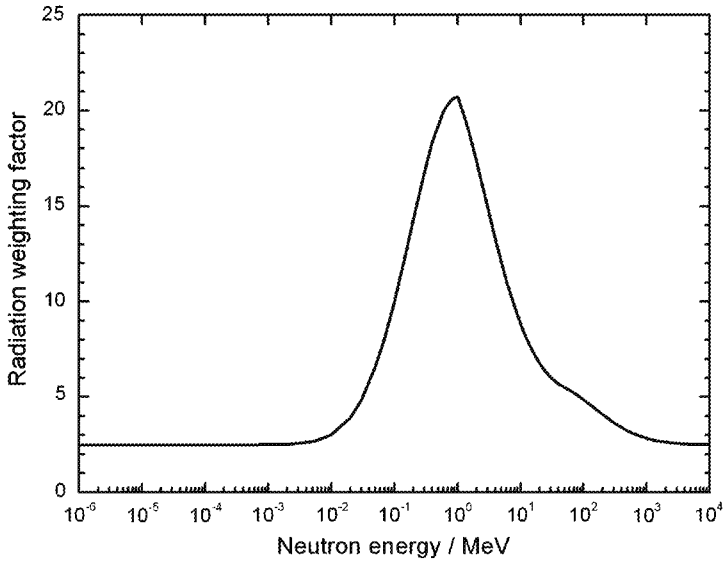

Fig. 1. Radiation weighting factor, w_R, for neutrons versus neutron energy.

(117) ***Neutrons.*** The radiation weighting factor for neutrons reflects their relative biological effectiveness following external exposure. The biological effectiveness of neutrons incident on the human body is strongly dependent on neutron energy (see Annex B).

(118) In *Publication 60* (ICRP, 1991b), the radiation weighting factor for neutrons was defined by a step function. It is now recommended that the radiation weighting factor for neutrons be defined by a continuous function (Fig. 1). It should be noted, however, that the use of a continuous function is based on the practical consideration that most neutron exposures involve a range of energies. The recommendation of the function does not imply a higher precision of the basic data. A detailed discussion on the selection of the w_R function for neutrons is given in Annex B. The most significant changes compared to the data in *Publication 60* are the decrease of w_R in the low-energy range, which takes account of the large contribution of secondary photons to the absorbed dose in the human body, and the decrease of w_R at neutron energies above 100 MeV. The following continuous function in neutron energy, E_n (MeV), is recommended for the calculation of radiation weighting factors for neutrons:

$$w_R = \begin{cases} 2.5 + 18.2e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases} \tag{4.3}$$

This function, i.e., Eq. (4.3) and Fig. 1, has been derived empirically and is consistent with existing biological and physical knowledge (Annex B).

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(119) ***Protons and pions.*** When considering exposure to protons, only external radiation sources are of importance in practical radiological protection. In the proton component of cosmic radiation fields or fields near high-energy particle accelerators, very high-energy protons dominate. Protons with energies of a few MeV are of minor significance even when their increased biological effectiveness at low energies is taken into account. It is judged to be sufficiently accurate for radiological protection purposes to adopt a single w_R value for protons of all energies that is mainly based on radiobiological data for high-energy protons above 10 MeV. The range of 10 MeV protons in tissue is 1.2 mm and decreases with lower energies. These protons will be absorbed in skin. (Annex B). A single radiation weighting factor of 2 is recommended for external proton radiation for general use (ICRP, 2003c). It replaces the value of 5 recommended in *Publication 60* (ICRP, 1991b).

(120) Pions are negatively or positively charged or neutral particles encountered in radiation fields resulting from interactions of primary cosmic rays with nuclei at high altitudes in the atmosphere. These particles contribute to exposures in aircraft. They are also found as part of the complex radiation fields behind shielding of high-energy particle accelerators and thus contribute to the occupational exposure of accelerator staff. Considering that the energy distribution of pions in radiation fields is very broad, the use of a single weighting factor of 2 is recommended for all charged pions.

(121) ***Alpha particles.*** Humans may be exposed to alpha particles from internal emitters, e.g., from inhaled radon progeny or ingested alpha-emitting radionuclides such as isotopes of plutonium, polonium, radium, thorium, and uranium. A number of epidemiological studies, as well as animal data, provide information on the risk from incorporated alpha emitters. However, the distribution of radionuclides in organs and tissues is complex and the estimation of dose depends on the models used. Hence the calculated doses are associated with substantial uncertainties and result in a broad range of RBE values from epidemiological as well as experimental studies (ICRP, 2003c, and Annex B).

(122) Despite substantial uncertainties in estimates of dose and risk from intakes of alpha-emitting radionuclides, the available human and animal data indicate that the RBE depends on the biological end-point under consideration. The limited human data that allow estimation of alpha particle RBE values suggest values of around 10–20 for lung and liver cancer and lower values for bone cancer and leukaemia. Judgements on the available data and the selection of a w_R value for alpha particles have been reviewed in *Publication 92* (ICRP, 2003c). As recent data do not provide compelling evidence for a change of the radiation weighting factor for alpha particles, the w_R value of 20 adopted in *Publication 60* (ICRP, 1991b) is retained.

(123) ***Fission fragments and heavy ions.*** Doses from fission fragments are of importance in radiological protection, mainly in internal dosimetry, and the situation regarding radiation weighting factors is similar to that for alpha particles. The short ranges of heavy ions and fission fragments in organs and tissues and the resulting ionisation density have a strong influence on their biological effectiveness. A radiation weighting factor of 20 (see Table 2), which equals that for alpha particles, is recommended (see Annex B).

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(124) Heavy ions are encountered in external radiation fields in aviation at high altitudes and in space exploration. Data on RBE for heavy ions are very limited and mostly based on in vitro experiments. The radiation quality of heavy charged particles incident on and stopped in the human body changes markedly along the track of the particle. The selection of a single w_R value of 20 for all types and energies of heavy charged particles is a conservative estimate and is recommended as sufficient for general application in radiological protection. For applications in space, where these particles contribute significantly to the total dose in the human body, a more realistic approach may have to be used.

4.3.4. Effective dose and tissue weighting factors

(125) The effective dose, E, introduced in *Publication 60* (ICRP, 1991b) is defined by a weighted sum of tissue equivalent doses as:

$$E = \sum_{T} w_T H_T = \sum_{T} w_T \sum_{R} w_R D_{T,R} \tag{4.4}$$

where w_T is the tissue weighting factor for tissue T and $\Sigma\ w_T = 1$. The sum is performed over all organs and tissues of the human body considered to be sensitive to the induction of stochastic effects. These w_T values are chosen to represent the contributions of individual organs and tissues to overall radiation detriment from stochastic effects. The unit of effective dose is J kg^{-1} with the special name sievert (Sv). The unit is the same for equivalent dose and effective dose as well as for some operational dose quantities (see Section 4.3.7). Care must be taken to ensure that the quantity being used is clearly stated.

(126) The organs and tissues for which w_T values are specified are given in Table 3 (see also Annex A).

(127) On the basis of epidemiological studies on cancer induction in exposed populations, and risk assessments for heritable effects, a set of w_T values was chosen for these Recommendations (Table 3) based on the respective values of relative radiation detriment (see Table 5 in Annex A). They represent mean values for humans averaged over both sexes and all ages and thus do not relate to the characteristics of particular individuals.

(128) The w_T for the remainder tissues (0.12) applies to the arithmetic mean dose of the 13 organs and tissues for each sex listed in the footnote to Table 3. The so-called splitting rule in the treatment of the remainder in *Publication 60* (ICRP, 1991b) is no longer used and hence the effective dose is additive.

4.3.5. Determination of effective dose

Reference phantoms

(129) The quantities equivalent dose and effective dose are not measurable in practice. For occupational exposures, their values are determined by radiation monitoring using operational quantities (see Section 4.3.6). For the calculation of conversion coefficients for external exposure, computational phantoms are used for dose assessment in

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various radiation fields. For the calculation of dose coefficients from intakes of radionuclides, biokinetic models for radionuclides, reference physiological data, and computational phantoms are used (see Annex B).

(130) The evaluation of equivalent doses for the Reference Male and Female and of effective dose for the Reference Person is based on the use of anthropomorphic models (phantoms). In the past, the Commission did not specify a particular phantom, and in fact various mathematical phantoms such as hermaphrodite MIRD-type phantoms (Snyder et al., 1969), the sex-specific models of Kramer et al. (1982), or the age-specific phantoms of Cristy and Eckerman (1987) have been used. The Commission now uses reference computational phantoms of the adult Reference Male and adult Reference Female for the calculation of equivalent doses for organs and tissues (Fig. 2). The phantoms are based on medical tomographic images (Zankl et al., 2005). They are made up of three-dimensional volume pixels (voxels). The voxels that make up defined organs have been adjusted to approximate the organ masses assigned to the Reference Male and Reference Female in *Publication 89* (ICRP, 2002). In order to provide a practicable approach for the assessment of equivalent doses and effective dose, conversion coefficients relating to physical quantities, e.g., particle fluence or air kerma for external exposure and activity intake for internal exposure, are calculated for standard exposure conditions for the reference phantoms.

(131) These models are computational representations of the Reference Male and Reference Female, and are used to compute the mean absorbed dose, D_T, in an organ or tissue T, from reference radiation fields external to the body and from decay of radionuclides after incorporation. They are used for calculations of dose conversion coefficients for external radiation fields and dose coefficients for the intake of radionuclides (see Annex B). These organ and tissue doses are multiplied with the radiation weighting factor to yield the equivalent doses in the tissues and organs of the Reference Male and the Reference Female (see Fig. 2). Reference computational phantoms will also be developed for children of different ages and for the pregnant woman and fetus.

Sex averaging for effective dose

(132) For the purposes of radiological protection, it is useful to apply a single value of effective dose for both sexes (see paragraph 33). The tissue weighting factors of Table 3 are sex- and age-averaged values for all organs and tissues, including the male and female breast, testis, and ovary (gonads: carcinogenic and heritable effects). This averaging implies that the application of this approach is restricted to the determination of effective dose in radiological protection and, in particular, cannot be used for the assessment of individual risk. The effective dose is then computed from the equivalent doses assessed for organ or tissue T of the Reference Male, H_T^M, and Reference Female, H_T^F, according to the following equation (see also Annex B):

$$E = \sum_T w_T \left[\frac{H_T^M + H_T^F}{2} \right] \tag{4.5}$$

(133) Analogous to the approach for other organs and tissues, the equivalent dose to the remainder is defined separately for the Reference Male and the Reference Female and these values are included in Eq. (4.5) – see Fig. 2. The equivalent dose

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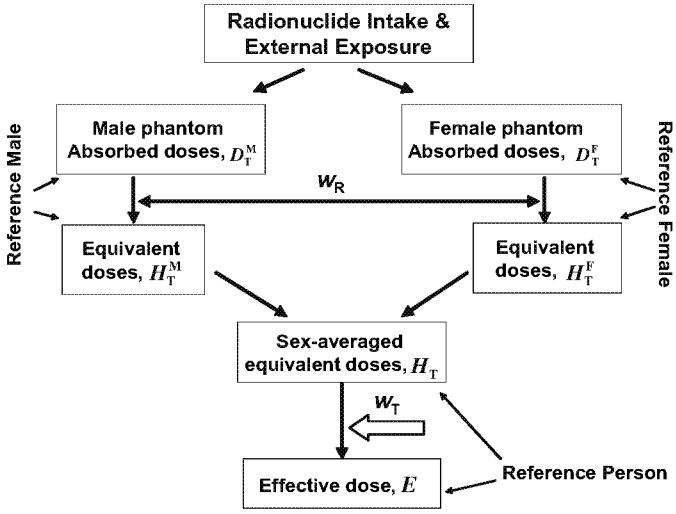

Fig. 2. Sex averaging to obtain the effective dose.

to the remainder tissues is computed as the arithmetic mean of the equivalent doses to the tissues listed in the footnote to Table 3. The equivalent doses to the remainder tissues of the Reference Male, $H_{\mathrm{rmd}}^{\mathrm{M}}$, and the Reference Female, $H_{\mathrm{rmd}}^{\mathrm{F}}$, are computed as

$$H_{\mathrm{rmd}}^{\mathrm{M}} = \frac{1}{13}\sum_{\mathrm{T}}^{13} H_{\mathrm{T}}^{\mathrm{M}} \quad \text{and} \quad H_{\mathrm{rmd}}^{\mathrm{F}} = \frac{1}{13}\sum_{\mathrm{T}}^{13} H_{\mathrm{T}}^{\mathrm{F}}. \tag{4.6}$$

where T is a remainder tissue from Table 3. The summation in Eqn. (4.5) extends over the equivalent dose to remainder tissues in the Reference Male and the Reference Female (Annex B).

(134) The effective dose for protection purposes is based on the mean doses in organs or tissues of the human body. It is defined and estimated in a Reference Person (see Fig. 2). This quantity provides a value which takes account of the given exposure conditions but not of the characteristics of a specific individual. In particular, the tissue weighting factors are mean values representing an average over many individuals of both sexes. The equivalent doses in the organs and tissues of the Reference Male and the Reference Female are averaged (Eqn. 4.5). The averaged dose is multiplied with the corresponding tissue weighting factor. The sum of these products yields the sex-averaged effective dose for the Reference Person (Fig. 2).

4.3.6. Operational quantities

(135) The body-related protection quantities, equivalent dose and effective dose, are not measurable in practice. Therefore, operational quantities are used for the

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assessment of effective dose or mean equivalent doses in tissues or organs. These quantities aim to provide a conservative estimate for the value of the protection quantities related to an exposure, or potential exposure, of persons under most irradiation conditions. They are often used in practical regulations or guidance. Different types of operational quantities are used for internal and external exposures as summarised below. More details are given in Annex B.

(136) Operational quantities for area and individual monitoring of external exposures have been defined by ICRU (see Annex B). The operational quantities for area monitoring are the ambient dose equivalent, $H^*(10)$ and the directional dose equivalent, $H'(0.07, \Omega)$. The operational quantity for individual monitoring is the personal dose equivalent, $H_p(d)$, which is the dose equivalent in ICRU (soft) tissue at an appropriate depth, d, below a specified point on the human body. The specified point is normally taken to be where the individual dosimeter is worn. For the assessment of effective dose, $H_p(10)$ with a depth $d = 10$ mm is chosen, and for the assessment of the dose to the skin and to the hands and feet the personal dose equivalent, $H_p(0.07)$, with a depth $d = 0.07$ mm, is used. A depth $d = 3$ mm has been proposed for the rare case of monitoring the dose to the lens of the eye. In practice, however, $H_p(3)$ has rarely been monitored and $H_p(0.07)$ can be used for the same monitoring purpose. Operational quantities are measurable, and instruments for radiation monitoring are calibrated in terms of these quantities. In routine monitoring, the values of these operational quantities are taken as a sufficiently precise assessment of effective dose and skin dose, respectively, in particular, if their values are below the protection limits.

(137) No operational quantities have been defined which provide a direct assessment of equivalent or effective dose for internal dosimetry. In general, various measurements of incorporated radionuclides are performed and biokinetic models are used in order to estimate the intake of radionuclides. From the intake, equivalent or effective dose is calculated by using reference dose coefficients (doses per unit intake, Sv Bq^{-1}) recommended by the Commission (see Annex B).

4.4. Assessment of radiation exposure

4.4.1. External radiation exposure

(138) The assessment of doses from exposure to radiation from external sources is usually performed either by individual monitoring using personal dosimeters worn on the body or, for example in cases of prospective assessments, by measuring or estimating $H^*(10)$ and applying appropriate conversion coefficients. The operational quantities for individual monitoring are $H_p(10)$ and $H_p(0.07)$. If the personal dosimeter is worn on a position of the body representative of its exposure, at low doses and under the assumption of a uniform whole-body exposure, the value of $H_p(10)$ provides an effective dose value sufficiently precise for radiological protection purposes.

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4.4.2. Internal radiation exposure

(139) The system of dose assessment for intakes of radionuclides relies on the calculation of the intake of a radionuclide, which can be considered as an operational quantity for the dose assessment from internal exposure. The intake can be estimated either from direct measurements (e.g., external monitoring of the whole body or of specific organs and tissues) or indirect measurements (e.g., urine or faeces), or measurements on environmental samples, and the application of biokinetic models. The effective dose is then calculated from the intake using dose coefficients recommended by the Commission for a large number of radionuclides. Dose coefficients are given for members of the public of various ages and for adults who are occupationally exposed.

(140) Radionuclides incorporated in the human body irradiate the tissues over time periods determined by their physical half-life and their biological retention within the body. Thus they may give rise to doses to body tissues for many months or years after the intake. The need to regulate exposures to radionuclides and the accumulation of radiation dose over extended periods of time has led to the definition of committed dose quantities. The committed dose from an incorporated radionuclide is the total dose expected to be delivered within a specified time period. The *committed equivalent dose*, $H_T(\tau)$, in a tissue or organ T is defined by:

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t)\mathrm{d}t \tag{4.7}$$

where τ is the integration time following the intake at time t_0. The quantity *committed effective dose* $E(\tau)$ is then given by:

$$E(\tau) = \sum_T w_T H_T(\tau) \tag{4.8}$$

(141) For compliance with dose limits, the Commission continues to recommend that the committed dose is assigned to the year in which the intake occurred. For workers, the committed dose is normally evaluated over the 50-year period following the intake. The commitment period of 50 years is a rounded value considered by the Commission to be the working-life expectancy of a young person entering the workforce. The committed effective dose from intakes of radionuclides is also used in prospective dose estimates for members of the public. In these cases, a commitment period of 50 years is recommended for adults. For infants and children, the dose is evaluated to the age of 70 years.

(142) The effective dose from occupational intakes of radionuclides is assessed on the basis of the worker's intake and the reference dose coefficient. The calculations of dose coefficients for specified radionuclides (Sv Bq^{-1}) use defined biokinetic and dosimetric models. Models are used to describe the entry of various chemical forms of radionuclides into the body and their distribution and retention after entering the blood. The computational male and female phantoms are also used to compute, for a series of sources, the fraction of the energy emitted from a source region S that is

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absorbed in target region T. These approximations are considered to be adequate for the main tasks in radiological protection.

(143) Sex-averaged committed effective dose coefficients $e(\tau)$[1] for the intake of specified radionuclides are calculated according to the equation:

$$e(\tau) = \sum_{\mathrm{T}} w_{\mathrm{T}} \left[\frac{h_{\mathrm{T}}^{\mathrm{M}}(\tau) + h_{\mathrm{T}}^{\mathrm{F}}(\tau)}{2} \right] \tag{4.9}$$

where w_{T} is the tissue weighting factor for tissue T, and $h_{\mathrm{T}}^{\mathrm{M}}(\tau)$ and $h_{\mathrm{T}}^{\mathrm{F}}(\tau)$ are the committed equivalent dose coefficients for tissue T of the male and female, respectively, for the commitment period τ. The summation in Eqn. (4.9) also extends over the committed equivalent dose coefficients for the remainder tissues in both the male and the female.

4.4.3. Occupational exposure

(144) In monitoring occupational exposures to external radiation, individual dosimeters measure the personal dose equivalent $H_{\mathrm{P}}(10)$. This measured value is taken as an assessment of the effective dose under the assumption of a uniform whole body exposure. For internal exposure, committed effective doses are generally determined from an assessment of the intakes of radionuclides from bioassay measurements or other quantities (e.g., activity retained in the body or in daily excreta). The radiation dose is determined from the intake using recommended dose coefficients (see Annex B).

(145) The doses obtained from the assessment of occupational exposures from external radiation and from intakes of radionuclides are combined for the assignment of the value of total effective dose, E, for demonstrating compliance with dose limits and constraints using the following formula:

$$E \cong H_{\mathrm{p}}(10) + E(50) \tag{4.10}$$

where $H_{\mathrm{p}}(10)$ is the personal dose equivalent from external exposure and $E(50)$, the committed effective dose from internal exposure, which is assessed by:

$$E(50) = \sum_{\mathrm{j}} e_{\mathrm{j,inh}}(50) \cdot I_{\mathrm{j,inh}} + \sum_{\mathrm{j}} e_{\mathrm{j,ing}}(50) \cdot I_{\mathrm{j,ing}} \tag{4.11}$$

where $e_{\mathrm{j,inh}}(50)$ is the committed effective dose coefficient for activity intakes by inhalation of a radionuclide j, $I_{\mathrm{j,inh}}$ is the activity intake of a radionuclide j by inhalation, $e_{\mathrm{j,ing}}(50)$ is the committed effective dose coefficient for activity intakes of a radionuclide j by ingestion, and $I_{\mathrm{j,ing}}$ is the activity intake of a radionuclide j by ingestion. In the calculation of the effective dose from specific radionuclides, allowance may need to be made for the characteristics of the material taken into the body.

[1] The lower case symbols e and h are used by convention to denote coefficients of the effective dose E and the equivalent dose H.

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(146) The dose coefficients used in Eqn. (4.11) are those specified by the Commission with no departure from the anatomical, physiological, and biokinetic characteristics of the Reference Male and the Reference Female (ICRP, 2002). Account may be taken of the physical and chemical characteristics of the intake, including the activity median aerodynamic diameter (AMAD) of the inhaled aerosol and the chemical form of the particulate matter to which the specified radionuclide is attached. The effective dose assigned in the worker's dose record is that value which the Reference Person would experience owing to the radiation fields and activity intakes encountered by the worker. The commitment period of 50 years represents the period of possible dose accumulation over a working life (this is only relevant for radionuclides with long physical half-lives and long retention in body tissues).

(147) The incorporation of radionuclides through uncontrolled events involving wounds has implications beyond compliance with work practices and thus these events are not included in Eqn. (4.11). The significance of these events must be evaluated and recorded, appropriate medical treatment provided, and further restriction of the worker's exposure considered if warranted.

(148) In the rare case of a significant contribution to external exposure of weakly-penetrating radiation, the contribution of the skin dose to the effective dose needs to be considered in addition to the terms given in Eq. (4.10) for the assessment of effective dose (see Annex B). The radiation dose from radon isotopes, primarily radon-222, and their decay products may also need to be taken into account in the overall dose assessment (ICRP 1993a).

(149) In certain situations where individual monitoring with personal dosimeters is not performed, such as exposure of aircrew, an assessment of effective dose may be obtained from values of the quantity ambient dose equivalent, $H^*(10)$. Effective dose in then calculated using appropriate factors derived from data on the radiation field, or by calculating effective dose directly from these data.

4.4.4. Public exposure

(150) The basic principles of estimation of effective doses are the same for members of the public as for workers. The annual effective dose to members of the public is the sum of the effective dose obtained within one year from external exposure and the committed effective dose from radionuclides incorporated within this year. The dose is not obtained by direct measurement of individual exposures as for occupational exposure but is mainly determined by effluent and environmental measurements, habit data, and modelling. The component due to discharges of radioactive effluents can be estimated by effluent monitoring for existing installations or prediction of effluents from the installation or source during the design period. Information on concentrations of radionuclides in effluents and the environment are used in conjunction with radioecological modelling (pathway analysis of environmental transport, through air, water, soil, sediments, plants, and animals to humans) to assess doses from external radiation exposure and intakes of radionuclides (see Annex B).

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4.4.5. Medical exposure of patients

(151) The relevant quantity for planning the exposure of patients and risk-benefit assessments is the equivalent dose or the absorbed dose to irradiated tissues. The use of effective dose for assessing the exposure of patients has severe limitations that must be considered when quantifying medical exposure. Effective dose can be of value for comparing doses from different diagnostic procedures and for comparing the use of similar technologies and procedures in different hospitals and countries as well as the use of different technologies for the same medical examination. However, for planning the exposure of patients and risk-benefit assessments, the equivalent dose or the absorbed dose to irradiated tissues is the relevant quantity.

(152) The assessment and interpretation of effective dose from medical exposure of patients is very problematic when organs and tissues receive only partial exposure or a very heterogeneous exposure which is the case especially with x-ray diagnostics.

4.4.6. Application of the effective dose

(153) The main and primary uses of effective dose in radiological protection for both occupational workers and the general public are:

- prospective dose assessment for planning and optimisation of protection; and
- retrospective dose assessment for demonstrating compliance with dose limits, or for comparing with dose constraints or reference levels.

(154) In this sense, effective dose is used for regulatory purposes worldwide. In practical radiological protection applications, effective dose is used for managing the risks of stochastic effects in workers and the public. The calculation of effective dose or corresponding conversion coefficients for external exposure, as well as dose coefficients for internal exposure, are based on absorbed dose, weighting factors (w_R and w_T), and reference values for the human body and its organs and tissues. Effective dose is not based on data from individual persons (see Annex B). In its general application, effective dose does not provide an individual-specific dose but rather that for a Reference Person under a given exposure situation.

(155) There may be some circumstances in which parameter values may be changed from the reference values in the calculation of effective dose. It is, therefore, important to distinguish between those reference parameter values that might be changed in the calculation of effective dose under particular circumstances of exposure and those values that cannot be changed under the definition of effective dose (e.g., the weighting factors). Thus, in the assessment of effective dose in occupational situations of exposure, changes may be made that, for example, relate to the characteristics of an external radiation field (e.g., direction of exposure) or to the physical and chemical characteristics of inhaled or ingested radionuclides. In such cases it is necessary to clearly state the deviation from the reference parameter values.

(156) In retrospective assessments of doses to specified individuals that may substantially exceed dose limits, effective dose can provide a first approximate measure of the overall detriment. If radiation dose and risk need to be assessed in a more

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accurate way, further specific estimates of organ or tissue doses are necessary, especially if organ-specific risks for the specified individuals are needed.

(157) Effective dose is intended for use as a protection quantity on the basis of reference values and therefore is not recommended for epidemiological evaluations, nor should it be used for detailed specific retrospective investigations of individual exposure and risk. Rather, absorbed dose should be used with the most appropriate biokinetic biological effectiveness and risk factor data. Organ or tissue doses, not effective doses, are required for assessing the probability of cancer induction in exposed individuals.

(158) The use of effective dose is inappropriate for the assessment of tissue reactions. In such situations it is necessary to estimate absorbed dose and to take into account the appropriate RBE as the basis for any assessment of radiation effects (see Annex B).

4.4.7. Collective effective dose

(159) For the purpose of optimisation of radiological protection, predominantly in the context of occupational exposure, the Commission has introduced collective dose quantities (ICRP 1977, 1991b). These quantities take account of the exposure of all individuals in a group over a given time period or during a given operation executed by this group in designated radiation areas. In practice, the collective equivalent dose is used only in special circumstances. The Commission therefore discusses only the collective effective dose quantity in these Recommendations. The collective effective dose, S (ICRP, 1991b) is calculated as the sum of all individual effective doses over the time period or during the operation being considered. The special name used for the collective effective dose quantity is the 'man sievert'. In the optimisation process, different radiological protection measures and operational scenarios are compared in terms of assessments of expected individual and collective effective doses.

(160) The collective effective dose, S, is based on the assumption of a linear dose effect relationship for stochastic effects without a threshold (the LNT model). On this basis it is possible to regard effective doses as additive.

(161) Collective effective dose is an instrument for optimisation, for comparing radiological technologies and protection procedures. Collective effective dose is not intended as a tool for epidemiological studies, and it is inappropriate to use it in risk projections. This is because the assumptions implicit in the calculation of collective effective dose (e.g., when applying the LNT model) conceal large biological and statistical uncertainties. Specifically, the computation of cancer deaths based on collective effective doses involving trivial exposures to large populations is not reasonable and should be avoided. Such computations based on collective effective dose were never intended, are biologically and statistically very uncertain, presuppose a number of caveats that tend not to be repeated when estimates are quoted out of context, and are an incorrect use of this protection quantity.

(162) To avoid inappropriate aggregation of, e.g., very low individual doses over extended time periods and wide geographical regions, limiting conditions need to be

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set. The dose range and the time period should be stated. The collective effective dose due to individual effective dose values between E_1 and E_2 is defined as:

$$S(E_1, E_2, \Delta T) = \int_{E_1}^{E_2} E\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\Delta T} \mathrm{d}E \tag{4.12}$$

where $(\mathrm{d}N/\mathrm{d}E)\mathrm{d}E$ denotes the number of individuals who are exposed to an effective dose between E and $E + \mathrm{d}E$ within the time period ΔT (see Annex B). When the range of individual doses spans several orders of magnitude, the distribution should be characterised by dividing it into several ranges of individual dose, each covering no more than two or three orders of magnitude, with the population size, mean individual dose, and uncertainty being considered separately for each range. When the collective effective dose is smaller than the reciprocal of the relevant risk detriment, the risk assessment should note that the most likely number of excess health effects is zero (NCRP 1995).

4.5. Uncertainties and judgements

(163) In the evaluation of radiation doses, models are necessary to simulate the geometry of the external exposure, the biokinetics of the intake and retention of radionuclides in the human body, and the human anatomy. In many cases, these models and their parameter values have been developed from experimental investigations and human studies in order to derive 'best estimates' or 'central estimates' of model parameter values. Similar considerations apply to the choice of tissue and radiation weighting factors. It is recognised that there are appreciable uncertainties in the values of some of the parameters and in the formulation or structures of the models themselves. Judgement is needed on the best choice of the necessary models and parameter values for dose assessments (see Annex B).

(164) Uncertainty refers to the level of confidence that can be placed in a given parameter value or prediction of a model. It is an important factor in all extrapolation procedures. In this connection the variability of individual parameters and the accuracy of measurements are also of great importance. The accuracy of measurements and judgements will become less with decreasing doses and increasing complexity of the system. Variability refers to quantitative differences between individual members of the population in question. All these aspects are taken into account in model development in the judgements made (see Annex B).

(165) The lack of certainty or precision in radiation dose models varies for the various parameters and the circumstances in defined situations. Therefore it is not possible to give values for the uncertainties across the range of ICRP models, despite the fact that their assessment is an important part of model development. Uncertainties may need to be assessed, however, for special cases, and approaches to their use have been described in a number of publications, e.g., Goossens et al. (1997), CERRIE (2004), ICRP (1994b, 2005d), Bolch et al. (2003), and Farfan et al. (2005). In general, it can be said that uncertainties of assessments of radiation doses from internal exposures, including the biokinetics of radionuclides, are larger than those from external exposures. The degree of uncertainty differs between various radionuclides.

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(166) The Commission is aware of the uncertainty or lack of precision in radiation dose models and efforts are undertaken to critically evaluate and to reduce them wherever possible. For regulatory purposes, the dosimetric models and parameter values that the Commission recommends are reference values. These are fixed by convention and are therefore not subject to uncertainty. Equally the Commission considers that the biokinetic and dosimetric models which are needed for the purpose of dose assessment are defined as reference data and, therefore, are also fixed and not applied with an uncertainty. These models and values are re-evaluated periodically and may be changed by ICRP on the basis of such evaluations when new scientific data and information are available.

(167) Regulatory compliance is determined using point estimates of effective dose that apply to a Reference Person, regarding these point estimates as subject to no uncertainties. In retrospective assessments of doses that may approach or exceed limits, it may be considered appropriate to make specific individual estimates of dose and risk, and also to consider uncertainties in these estimates.

(168) Despite changes in dosimetric modelling, as well as differences in the computation of effective dose, previous assessments of equivalent dose or effective dose should be considered adequate. In general, the Commission does not recommend re-computation of existing values with the new models and parameters.

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5. THE SYSTEM OF RADIOLOGICAL PROTECTION OF HUMANS

(169) Everybody is exposed to ionising radiation from natural and man-made sources. It is convenient to think of the processes causing these human exposures as a *network of events and situations*. Each part of the network starts from a source. Radiation or radioactive material then passes through environmental or other pathways leading to the exposure of individuals. Finally, the exposure of individuals to radiation or radioactive materials leads to doses to these individuals. Protection can be achieved by taking action at the source, or at points in the exposure pathways, and occasionally by modifying the location or characteristics of the exposed individuals. For convenience, the environmental pathway is usually taken to include the link between the source of exposure and the doses received by the individuals. The available points of action have a substantial effect on the system of protection.

(170) The assumed proportional relationship between an increment of dose and an increment of risk of stochastic effects makes it possible to deal separately with different parts of this network of events and situations leading to exposure, and to select those parts that are of relevance in a given situation. To make these selections, however, it is necessary to define, for each part of the network, the objectives, the organisations (and individuals) responsible for protection, the lines of responsibility, and the feasibility of obtaining the necessary information. This remains a complex procedure, and the Commission suggests two simplifications in managing radiological situations.

(171) The first simplification was used in the 1990 Recommendations and recognises that individuals are subject to several categories of exposure, which can be dealt with separately (ICRP, 1991b). For example, most workers who are exposed to radiation sources as part of their work are also exposed to environmental sources as members of the public, and to medical exposure as patients. The Commission's policy continues to be that the control of exposures due to work need not be influenced by the exposures from these other sources. This policy is still generally reflected in the present Recommendations by the separation of the exposure into three categories (see Section 5.3): occupational exposure, medical exposure of patients, and public exposure. The Commission continues to recommend that, for regulatory purposes, no attempt be made to add the exposures to the same individual from the different categories of exposure.

(172) The second simplification is that, in dealing with the network constituting a variety of exposure pathways, a distinction is drawn between source-related considerations and individual-related considerations (see Section 5.5). Although within each category of exposure individuals can be exposed to several sources, for the purposes of radiological protection each source, or group of sources, can be treated on its own (ICRP, 1991b). It is then necessary to consider the exposure of all the individuals who could be exposed by this source or group of sources. This procedure is called a 'source-related assessment'.

(173) For the practical control of exposures, in *Publication 60* the network of events and situations causing these exposures was divided into two broad classes

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of situations: practices and interventions. Practices were defined as human actions increasing exposure either by introducing whole new blocks of sources, pathways, and individuals, or by modifying the network of pathways from existing sources to individuals and thus increasing the exposure of individuals or the number of individuals so exposed. Interventions were defined as human actions that decrease the overall exposure by influencing the existing form of the network. These activities may remove existing sources, modify pathways or reduce the number of exposed individuals. In the revised system of protection the Recommendations of the Commission have now evolved from a process-based approach to an approach based on the characteristics of three types of radiation exposure situation, i.e., planned, emergency, and existing exposure situations (see Section 5.2).

5.1. The definition of a source

(174) The Commission uses the term 'source' to indicate any physical entity or procedure that results in a potentially quantifiable radiation dose to a person or group of persons. It can be a physical source (e.g., radioactive material or an x-ray machine), an installation (e.g., a hospital or a nuclear power plant), or procedures or groups of physical sources having similar characteristics (e.g., nuclear medicine procedures or background or environmental radiation). If radioactive substances are released from an installation into the environment, the installation as a whole may be regarded as a source; if they are already dispersed in the environment, the portion of them to which people are exposed may be considered a source. Most situations will give rise to a predominant source of exposure for any single individual, making it possible to treat sources singly when considering actions.

(175) In general, the definition of a source will be linked to the selection of the relevant protection strategy, as appropriate, for optimisation. Difficulties will arise if the policy is distorted, e.g., by artificially subdividing a source in order to avoid the need for protective action, or by excessively aggregating sources to exaggerate the need for action. Provided that the regulatory authority and the user (where one can be defined) both apply the spirit of the Commission's broad policies, practical agreements can be reached on the definition of a source.

5.2. Types of exposure situations

(176) The Commission intends its Recommendations to be applied to all sources and to individuals exposed to radiation in the following three types of exposure situations which address all conceivable circumstances.

- *Planned exposure situations* are situations involving the deliberate introduction and operation of sources. Planned exposure situations may give rise both to exposures that are anticipated to occur (normal exposures) and to exposures that are not anticipated to occur (potential exposures; see Section 6.1.3).
- *Emergency exposure situations* are situations that may occur during the operation of a planned situation, or from a malicious act, or from any other unexpected

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situation, and require urgent action in order to avoid or reduce undesirable consequences.

- *Existing exposure situations* are exposure situations that already exist when a decision on control has to be taken, including prolonged exposure situations after emergencies.

It follows that what the Commission has called 'practices' could be the origin of planned, emergency, and existing exposure situations. Medical exposures of patients are also planned exposure situations, but because of the characteristics of such exposures, they are discussed separately. The principles of protection for planned situations also apply to occupational exposure in connection with existing and emergency exposure situations.

5.3. Categories of exposure

(177) The Commission distinguishes between three categories of exposures: occupational exposures, public exposures, and medical exposures of patients. Exposures of comforters and carers, and exposures of volunteers in research, are discussed in Chapter 7.

5.3.1. Occupational exposure

(178) Occupational exposure is defined by the Commission as all radiation exposure of workers incurred as a result of their work. The Commission has noted the conventional definition of occupational exposure to any hazardous agent as including all exposures at work, regardless of their source. However, because of the ubiquity of radiation, the direct application of this definition to radiation would mean that all workers should be subject to a regime of radiological protection. The Commission therefore limits its use of 'occupational exposures' to radiation exposures incurred at work as a result of situations that can reasonably be regarded as being the responsibility of the operating management (see also Section 6.3.1). Excluded exposures and exposures from exempt practices or exempt sources generally do not need to be accounted for in occupational protection.

(179) The employer has the main responsibility for the protection of workers. However, the licensee responsible for the source (if not identical to the employer) also has a responsibility for the radiological protection of workers. If workers are engaged in work that involves, or could involve, a source that is not under the control of their employer, the licensee and the employer should co-operate by the exchange of information and otherwise as necessary to facilitate proper radiological protection at the workplace.

5.3.2. Public exposure

(180) Public exposure encompasses all exposures of the public other than occupational exposures and medical exposures of patients (see Section 5.3.3). It is incurred

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as a result of a range of radiation sources. The component of public exposure due to natural sources is by far the largest, but this provides no justification for reducing the attention paid to smaller, but more readily controllable, exposures to man-made sources. Exposures of the embryo and fetus of pregnant workers are considered and regulated as public exposures.

5.3.3. Medical exposure of patients

(181) Radiation exposures of patients occur in diagnostic, interventional, and therapeutic procedures. There are several features of radiological practices in medicine that require an approach that differs from the radiological protection in other planned exposure situations. The exposure is intentional and for the direct benefit of the patient. Particularly in radiotherapy, the biological effects of high-dose radiation, e.g., cell killing, are used for the benefit of the patient to treat cancer and other diseases. The application of these Recommendations to the medical uses of radiation therefore requires separate guidance (see Chapter 7, which also discusses the medical exposure of comforters and carers and of volunteers in research).

5.4. The identification of the exposed individuals

(182) It is necessary to deal separately with at least three categories of exposed individuals, namely workers, the public, and patients. They essentially correspond to individuals whose exposures fall into the three categories of exposure defined in Section 5.3. A given individual may be exposed as a worker, and/or as a member of the public, and/or as a patient.

5.4.1. Workers

(183) A worker is defined by the Commission as any person who is employed, whether full time, part time, or temporarily, by an employer and who has recognised rights and duties in relation to occupational radiological protection. A self-employed person is regarded as having the duties of both an employer and a worker. Workers in medical professions involving radiation are occupationally exposed.

(184) One important function of an employer and/or licensee is that of maintaining control over the sources of exposure and over the protection of workers who are occupationally exposed. In order to achieve this, the Commission continues to recommend the classification of areas of work rather than the classification of workers. Requiring that the areas of workplaces containing sources be formally designated helps their control. The Commission uses two such designations: *controlled areas* and *supervised areas*. A controlled area is a defined area in which specific protection measures and safety provisions are, or could be, required for controlling normal exposures or preventing the spread of contamination during normal working conditions, and preventing or limiting the extent of potential exposures. A supervised area is one in which the working conditions are kept under review but special procedures

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are not normally needed. A controlled area is often within a supervised area, but need not be.

(185) Workers in 'controlled areas' of workplaces should be well informed and specially trained, and form a readily identifiable group. Such workers are most often monitored for radiation exposures incurred in the workplace, and occasionally may receive special medical surveillance.

The exposure of pregnant or breast-feeding workers

(186) In the 1990 Recommendations, the Commission concluded that, for the purpose of controlling occupational exposure, there was no reason to distinguish between the two sexes. The Commission maintains this policy with these Recommendations. However, if a female worker has declared (i.e., notified her employer) that she is pregnant, additional controls have to be considered to protect the embryo/fetus. It is the Commission's policy that the methods of protection at work for women who are pregnant should provide a level of protection for the embryo/fetus broadly similar to that provided for members of the public. The Commission considers that this policy will be adequately applied if the mother is exposed, prior to her declaration of pregnancy, under the system of protection recommended by the Commission. Once an employer has been notified of a pregnancy, additional protection of the embryo/fetus should be considered. The working conditions of a pregnant worker, after declaration of pregnancy, should be such as to ensure that the additional dose to the embryo/fetus would not exceed about 1 mSv during the remainder of the pregnancy. Additional guidance on protection of an embryo/fetus exposed to radiation is provided in Section 7.4.

(187) The restriction of the dose to the embryo/fetus does not mean that it is necessary for pregnant women to avoid work with radiation or radioactive materials completely, or that they must be prevented from entering or working in designated radiation areas (see paragraph 184). It does, however, imply that the employer should carefully review the exposure conditions of pregnant women. In particular, if required, their working conditions should be changed such that, during pregnancy, the probability of accidental doses and radionuclide intakes is extremely low. Specific recommendations on the control of exposures to pregnant workers are given in *Publications 84* and *88* (ICRP, 2000a, 2001a). The Commission has also published information in *Publication 95* (ICRP, 2004c) that enables doses to offspring following intakes to breast-feeding mothers to be calculated. The Commission strongly recommends that in order to protect the embryo/fetus or infant, females who have declared that they are pregnant or are nursing should not be involved in emergency actions involving high radiation doses (ICRP, 2005a).

(188) In *Publication 88* (ICRP, 2001a), the Commission gave dose coefficients for the embryo, fetus, and newborn child from intakes of radionuclides by the mother before or during pregnancy. In general, doses to the embryo, fetus, and newborn child are similar to or less than those to the Reference Female. In *Publication 95* (ICRP, 2004c) the Commission provided information on radiation doses to the breast-feeding infant due to intakes of radionuclides in maternal milk. For most of the radionuclides

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considered, doses to the infant from radionuclides ingested in breast milk are estimated to be small in comparison with doses to the Reference Female.

Exposures in aviation and in space

(189) In *Publication 60* (ICRP, 1991b), the Commission recommended that exposures to cosmic radiation be part of occupational exposure in the operation of commercial jet aircraft and space flight. The Commission subsequently clarified its recommendation in *Publication 75* (ICRP, 1997a), indicating that it is not necessary to treat the exposure of frequent-flyer passengers as occupationally exposed for the purpose of control. Thus, essentially, only aircrew should be considered. At that time, the Commission had already noted that the only practical regulatory measures were controlling individual exposure through the control of flying time and route selection. The Commission maintains this view.

(190) Exceptional cases of cosmic radiation exposures, such as exposure in space travel, where doses may be significant and some type of control warranted, should be dealt with separately, taking into account the special type of situations that can give rise to this type of exposure.

5.4.2. Members of the public

(191) A member of the public is defined by the Commission as any individual who receives an exposure that is neither occupational nor medical (see also Section 5.4.3). A large range of different natural and man-made sources contribute to the exposure of members of the public.

(192) In general, especially for public exposure, each source will result in a distribution of doses over many individuals. For the purposes of protection of the public, the Commission has used the 'critical group' concept to characterise an individual receiving a dose that is representative of the more highly exposed individuals in the population (ICRP, 1977). Dose restrictions have been applied to the mean dose in the appropriate critical group. Over the past decades, a considerable body of experience has been gained in the application of the critical group concept. There have also been developments in the techniques used to assess doses to members of the public, notably the increasing use of probabilistic techniques. The adjective 'critical' has the connotation of a crisis, which was never intended by the Commission. Furthermore, the word 'group' may be confusing in the context where the assessed dose is to an individual.

(193) The Commission now recommends the use of the 'Representative Person' for the purpose of radiological protection of the public instead of the earlier critical group concept. The Commission provides guidance on characterising the Representative Person and assessing doses to the Representative Person in *Publication 101* (ICRP, 2006a).

(194) The Representative Person may be hypothetical, but it is important that the habits (e.g., consumption of foodstuffs, breathing rate, location, usage of local resources) used to characterise the Representative Person are typical habits of a small number of individuals representative of those most highly exposed and not the extreme habits of a single member of the population. Consideration may be given

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to some extreme or unusual habits, but they should not dictate the characteristics of the Representative Persons considered.

5.4.3. Patients

(195) The Commission defines the patient as an individual who receives an exposure associated with a diagnostic, interventional, or therapeutic procedure. The Commission's dose limits and dose constraints are not recommended for individual patients because they may reduce the effectiveness of the patient's diagnosis or treatment, thereby doing more harm than good. The emphasis is therefore on the justification of the medical procedures and on the optimisation of protection and, for diagnostic procedures, the use of diagnostic reference levels (see Chapter 7).

(196) The exposure of patients who are pregnant is dealt with in Section 7.4.

5.5. Levels of radiological protection

(197) In the 1990 Recommendations it was noted that, provided that individual doses are well below the thresholds for harmful deterministic effects, the effect of a contribution to an individual dose from a source is independent of the effects of doses from other sources. For many purposes, each source or group of sources could usually be treated on its own. It is then necessary to consider the exposure of individuals exposed by this source or group of sources. This procedure is called a 'source-related' approach. The Commission now emphasises the primary importance of the source-related approach, because action can be taken on a source to assure the protection of a group of individuals from that source.

(198) For planned exposure situations, the source-related restriction to the dose that individuals may incur is the *dose constraint*. For potential exposures, the corresponding concept is the *risk constraint*. For emergency and existing exposure situations, the source-related restriction is the *reference level* (see Sections 5.9, 6.2, and 6.3). The concepts of a dose constraint and reference level are used in the process of optimisation of protection to assist in ensuring that all exposures are kept as low as reasonably achievable, societal and economic factors being taken into account. Constraints and reference levels can thus be described as key parts in the optimisation process that will ensure appropriate levels of protection under the prevailing circumstances.

(199) It could be argued that the source-related restriction would not provide sufficient protection where there are multiple sources. However, the Commission presumes that there will generally be a dominant source, and the selection of the appropriate reference level or constraint ensures an adequate level of protection. The Commission still considers that the source-related principle of optimisation below the constraint or reference level is the most effective tool for protection, whatever the situation.

(200) In the specific case of planned exposure situations, separate restrictions on the sums of the occupational doses and on the sums of the public doses are required. The Commission refers to such individual-related restrictions as dose limits (see Section 5.10) and the corresponding assessment of doses is called 'individual-related'.

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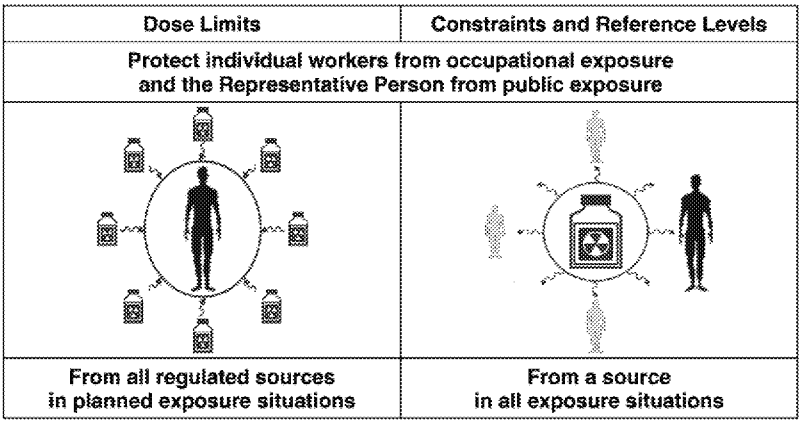

Fig. 3. Dose limits contrasted with dose constraints and reference levels for protecting workers and members of the public.

(201) It is rarely possible, however, to assess the total exposure of an individual from all such sources. It is therefore necessary to make approximations to the dose to be compared with the quantitative limit, especially in the case of public exposure. For occupational exposures, the approximations are more likely to be accurate because the operating management has access to the necessary information to identify and control the dose from all the relevant sources.

(202) Figure 3 illustrates the differences in concept between the use of individual dose limits in planned situations and constraints or reference levels for protection from a source in all situations.

5.6. The principles of radiological protection

(203) In the 1990 Recommendations, the Commission gave principles of protection for practices separately from intervention situations. The Commission continues to regard these principles as fundamental for the system of protection, and has now formulated a single set of principles that apply to planned, emergency, and existing exposure situations. In these Recommendations, the Commission also clarifies how the fundamental principles apply to radiation sources and to the individual, as well as how the source-related principles apply to all controllable situations.

Two principles are source-related and apply in all exposure situations

- **The principle of justification:** Any decision that alters the radiation exposure situation should do more good than harm.

This means that, by introducing a new radiation source, by reducing existing exposure, or by reducing the risk of potential exposure, one should achieve sufficient individual or societal benefit to offset the detriment it causes.

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- **The principle of optimisation of protection:** the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.

This means that the level of protection should be the best under the prevailing circumstances, maximising the margin of benefit over harm. In order to avoid severely inequitable outcomes of this optimisation procedure, there should be restrictions on the doses or risks to individuals from a particular source (dose or risk constraints and reference levels).

One principle is individual-related and applies in planned exposure situations

- **The principle of application of dose limits:** The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits recommended by the Commission.

(204) Regulatory dose limits are determined by the regulatory authority, taking account of international recommendations, and apply to workers and to members of the public in planned exposure situations.

5.7. Justification

(205) The Commission recommends that, when activities involving an increased or decreased level of radiation exposure, or a risk of potential exposure, are being considered, the expected change in radiation detriment should be explicitly included in the decision-making process. The consequences to be considered are not confined to those associated with the radiation – they include other risks and the costs and benefits of the activity. Sometimes, the radiation detriment will be a small part of the total. Justification thus goes far beyond the scope of radiological protection. It is for these reasons that the Commission only recommends that justification require that the net benefit be positive. To search for the best of all the available alternatives is a task beyond the responsibility of radiological protection authorities.

5.7.1. Application of the principle of justification

(206) There are two different approaches to applying the principle of justification in situations involving occupational and public exposure, which depend upon whether or not the source can be directly controlled. The first approach is used in the introduction of new activities where radiological protection is planned in advance and the necessary actions can be taken on the source. Application of the justification principle to these situations requires that no planned exposure situation should be introduced unless it produces sufficient net benefit to the exposed individuals or to society to offset the radiation detriment it causes. Judgements on whether it would be justifiable to introduce or continue particular types of planned situation

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involving exposure to ionising radiation are important. The justification may need to be re-examined as new information or technology becomes available.

(207) The second approach is used where exposures can be controlled mainly by action to modify the pathways of exposure and not by acting directly on the source. The main examples are existing exposure situations and emergency exposure situations. In these circumstances, the principle of justification is applied in making the decision as to whether to take action to avert further exposure. Any decision taken to reduce doses, which always have some disadvantages, should be justified in the sense that they should do more good than harm.

(208) In both approaches, the responsibility for judging the justification usually falls on governments or national authorities to ensure an overall benefit in the broadest sense to society and thus not necessarily to each individual. However, input to the justification decision may include many aspects that could be informed by users or other organisations or persons outside of government. As such, justification decisions will often be informed by a process of public consultation, depending upon, among other things, the size of the source concerned. There are many aspects of justification, and different organisations may be involved and responsible. In this context, radiological protection considerations will serve as one input to the broader decision process.

(209) Medical exposure of patients calls for a different and more detailed approach to the process of justification. The medical use of radiation should be justified, as is any other planned exposure situation, although that justification lies more often with the profession than with government or the competent regulatory authority. The principal aim of medical exposures is to do more good than harm to the patient, due account being taken of the radiation detriment from the exposure of the radiological staff and of other individuals. The responsibility for the justification of the use of a particular procedure falls on the relevant medical practitioners, who need to have special training in radiological protection. Justification of medical procedures therefore remains part of the Commission's Recommendations (see Section 7.1).

5.7.2. Unjustified exposures

(210) The Commission considers that certain exposures should be deemed to be unjustified without further analysis, unless there are exceptional circumstances. These include the following:

- Increasing, by deliberate addition of radioactive substances or by activation, the activity of products such as food, beverages, cosmetics, toys, and personal jewellery or adornments.
- Radiological examination for occupational, health insurance, or legal purposes undertaken without reference to clinical indications, unless the examination is expected to provide useful information on the health of the individual examined or in support of important criminal investigations. This almost always means that a clinical evaluation of the image acquired must be carried out, otherwise the exposure is not justified.

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- Medical screening of asymptomatic population groups involving radiation exposure, unless the expected advantages for the individuals examined or for the population as a whole are sufficient to compensate for the economic and societal costs, including the radiation detriment. Account should be taken of the potential of the screening procedure for detecting disease, the likelihood of effective treatment of cases detected, and, for certain diseases, the advantages to the community of control of the disease.

5.8. Optimisation of protection

(211) The process of optimisation of protection is intended for application to those situations that have been deemed to be justified. The principle of optimisation of protection, with restriction on the magnitude of individual dose or risk, is central to the system of protection and applies to all three exposure situations: planned exposure situations, emergency exposure situations, and existing exposure situations.

(212) The principle of optimisation is defined by the Commission as the source-related process to keep the likelihood of incurring exposures (where these are not certain to be received), the number of people exposed, and the magnitude of individual doses as low as reasonably achievable, taking economic and societal factors into account.

(213) The Recommendations of the Commission on how to apply the optimisation principle have been provided earlier (ICRP, 1983, 1989, 1991b, and 2006a), and these Recommendations remain valid and will not be repeated in detail here. The decision-aiding techniques are still essential to find the optimised radiological protection solution in an objective manner; these techniques include methods for quantitative optimisation such as cost-benefit analyses. The process of optimisation over the past decades has resulted in substantial reductions of occupational and public exposures.

(214) Optimisation is always aimed at achieving the best level of protection under the prevailing circumstances through an ongoing, iterative process that involves:

- evaluation of the exposure situation, including any potential exposures (the framing of the process);
- selection of an appropriate value for the constraint or reference level;
- identification of the possible protection options;
- selection of the best option under the prevailing circumstances; and
- implementation of the selected option.

(215) Experience has shown how optimisation of protection has improved radiological protection for planned situations. Constraints provide a desired upper bound for the optimisation process. Some sources and technologies are able to satisfy constraints that are set at a low level, while others are only able to meet constraints set at a higher level. This is normal and should be reflected in the freedom of regulatory authorities and others, as appropriate, to select values that are appropriate for particular circumstances.

(216) In all situations, the process of optimisation with the use of constraints or reference levels is applied in planning protective actions and in establishing the

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appropriate level of protection under the prevailing circumstances. The doses to be compared with the dose constraint or reference levels are usually prospective doses, i.e., doses that may be received in the future, as it is only those doses that can be influenced by decisions on protective actions. They are not intended as a form of retrospective dose limit.

(217) The optimisation of protection is a forward-looking iterative process aimed at preventing or reducing future exposures. It takes into account both technical and socio-economic developments and requires both qualitative and quantitative judgements. The process should be systematic and carefully structured to ensure that all relevant aspects are taken into account. Optimisation is a frame of mind, always questioning whether the best has been done in the prevailing circumstances, and whether all that is reasonable has been done to reduce doses. It also requires commitment at all levels in all concerned organisations as well as adequate procedures and resources.

(218) The best option is always specific to the exposure situation and represents the best level of protection that can be achieved under the prevailing circumstances. Therefore it is not relevant to determine, a priori, a dose level below which the optimisation process should stop. Depending on the exposure situation, the best option could be close to or well below the appropriate source-related constraint or reference level.

(219) Optimisation of protection is not minimisation of dose. Optimised protection is the result of an evaluation, which carefully balances the detriment from the exposure and the resources available for the protection of individuals. Thus the best option is not necessarily the one with the lowest dose.

(220) In addition to the reduction of the magnitude of individual exposures, a reduction of the number of exposed individuals should also be considered. The collective effective dose has been and remains a key parameter for optimisation of protection for workers. The comparison of protection options for the purpose of optimisation must entail a careful consideration of the characteristics of the individual exposure distribution within an exposed population.

(221) When exposures occur over large populations, large geographical areas, or long time periods, the total collective effective dose is not a useful tool for making decisions because it may aggregate information inappropriately and could be misleading for selecting protective actions. To overcome the limitations associated with collective effective dose, each relevant exposure situation must be carefully analysed to identify the individual characteristics and exposure parameters that best describe the exposure distribution among the concerned population for the particular circumstance. Such an analysis – by asking when, where and by whom exposures are received – results in the identification of various population groups with homogeneous characteristics for which collective effective doses can be calculated within the optimisation process, and for which an optimised protection strategy can be defined (see Section 4.4). In practical optimisation assessments, collective doses may often be truncated, because the assessments use the difference between the integrals defining the collective doses assigned to the various alternative protective options under consideration, rather than the full integrals (ICRP, 1983).

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(222) In *Publications 77* and *81* (ICRP, 1997d, 1998b), the Commission recognised that both the individual doses and the size of the exposed population become increasingly uncertain as time increases. The Commission is of the opinion that in the decision-making process, owing to the increasing uncertainties, giving less weight to very low doses and to doses received in the distant future could be considered (see also Section 4.4.7). The Commission does not intend to give detailed guidance on such weighting, but rather stresses the importance of demonstrating in a transparent manner how any weighting has been carried out.

(223) All aspects of optimisation cannot be codified; rather, there should be a commitment by all parties to the optimisation process. Where optimisation becomes a matter for the regulatory authority, the focus should not be on specific outcomes for a particular situation, but rather on processes, procedures, and judgements. An open dialogue should be established between the authority and the operating management, and the success of the optimisation process will depend strongly on the quality of this dialogue.

(224) Societal values usually influence the final decision on the level of radiological protection. Therefore, while this report should be seen as providing decision-aiding recommendations mainly based on scientific considerations on radiological protection, the Commission's advice will be expected to serve as an input to a final (usually wider) decision-making process, which may include other societal concerns and ethical aspects, as well as considerations of transparency (ICRP, 2006a). This decision-making process may often include the participation of relevant stakeholders rather than radiological protection specialists alone.

5.9. Dose constraints and reference levels

(225) The concepts of *dose constraint* and *reference level* are used in conjunction with the optimisation of protection to restrict individual doses. A level of individual dose, either as a dose constraint or a reference level, always needs to be defined. The initial intention would be to not exceed, or to remain at, these levels, and the ambition is to reduce all doses to levels that are as low as reasonably achievable, economic and societal factors being taken into account.

(226) For the sake of continuity with its earlier Recommendations (ICRP, 1991b), the Commission retains the term 'dose constraint' for this level of dose in planned exposure situations (with the exception of medical exposure of patients). For emergency exposure situations and existing exposure situations, the Commission proposes the term 'reference level' to describe this level of dose. The difference in terminology between planned and other exposure situations (emergency and existing) has been retained by the Commission to express the fact that, in planned situations, the restriction on individual doses can be applied at the planning stage, and the doses can be forecast so as to ensure that the constraint will not be exceeded. With the other situations a wider range of exposures may exist, and the optimisation process may apply to initial levels of individual doses above the reference level.

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Table 4. The dose constraints and reference levels used in the Commission's system of protection.

Type of situation	Occupational exposure	Public exposure	Medical exposure
Planned exposure	Dose limit Dose constraint	Dose limit Dose constraint	Diagnostic reference level[d] (Dose constraint[e])
Emergency exposure	Reference level[a]	Reference level	N.A.[b]
Existing exposure	N.A.[c]	Reference level	N.A.[b]

[a] Long-term recovery operations should be treated as part of planned occupational exposure.
[b] Not applicable.
[c] Exposures resulting from long-term remediation operations or from protracted employment in affected areas should be treated as part of planned occupational exposure, even though the source of radiation is 'existing'.
[d] Patients.
[e] Comforters, carers, and volunteers in research only (see Sections 7.6 and 7.7).

(227) Diagnostic reference levels are already being used in medical diagnosis (i.e., planned exposure situations) to indicate whether, in routine conditions, the levels of patient dose or administered activity from a specified imaging procedure are unusually high or low for that procedure. If so, a local review should be initiated to determine whether protection has been adequately optimised or whether corrective action is required.

(228) The chosen value for a constraint or a reference level will depend upon the circumstances of the exposure under consideration. It must also be realised that neither dose and risk constraints nor reference levels represent a demarcation between 'safe' and 'dangerous' or reflect a step change in the associated health risk for individuals.

(229) In Table 4 the different types of dose restrictions used in the Commission's system of protection (limits, constraints, reference levels) are shown in relation to type of exposure situation and category of exposure. In planned exposure situations, there are also risk constraints in order to take account of potential exposures.

5.9.1. Dose constraints

(230) A dose constraint is a prospective and source-related restriction on the individual dose from a source in planned exposure situations (except in medical exposure of patients), which serves as an upper bound on the predicted dose in the optimisation of protection for that source. It is a level of dose above which it is unlikely that protection is optimised for a given source of exposure, and for which, therefore, action must almost always be taken. Dose constraints for planned situations represent a basic level of protection and will always be lower than the pertinent dose limit. During planning it must be ensured that the source concerned does not imply doses exceeding the constraint. Optimisation of protection will establish an acceptable level of dose below the constraint. This optimised level then becomes the expected outcome of the planned protective actions.

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(231) The action necessary if a dose constraint is exceeded includes determining whether protection has been optimised, whether the appropriate dose constraint has been selected, and whether further steps to reduce doses to acceptable levels would be appropriate. For potential exposures, the corresponding source-related restriction is called a risk constraint (see Section 6.1.3). Treating a dose constraint as a target value is not sufficient, and optimisation of protection will be necessary to establish an acceptable level of dose below the constraint.

(232) The concept of dose constraints was introduced in *Publication 60* as a means of ensuring that the optimisation process did not create inequity, i.e., the possibility that some individuals in an optimised protection scheme may be subject to much more exposure than the average:

> '*Most of the methods used in the optimisation of protection tend to emphasise the benefits and detriments to society and the whole exposed population. The benefits and detriments are unlikely to be distributed through society in the same way. Optimisation of protection may thus introduce a substantial inequity between one individual and another. This inequity can be limited by incorporating source-related restrictions on individual dose into the process of optimization. The Commission calls these source-related restrictions dose constraints, previously called upper bounds. They form an integral part of the optimization of protection. For potential exposures, the corresponding concept is the risk constraint.*' (ICRP, 1991b)

This statement continues to represent the Commission's view.

(233) For occupational exposures, the dose constraint is a value of individual dose used to limit the range of options such that only options expected to cause doses below the constraint are considered in the process of optimisation. For public exposure, the dose constraint is an upper bound on the annual doses that members of the public could receive from the planned operation of a specified controlled source. The Commission wishes to emphasise that dose constraints are not to be used or understood as prescriptive regulatory limits.

5.9.2. Reference levels

(234) In emergency or existing controllable exposure situations, the reference levels represent the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur (cf. Section 6.2), and for which therefore protective actions should be planned and optimised. The chosen value for a reference level will depend upon the prevailing circumstances of the exposure situation under consideration.

(235) When an emergency exposure situation has occurred, or an existing exposure situation has been identified, and protective actions have been implemented, doses to workers and members of the public can be measured or assessed. The reference level may then assume a different function as a benchmark against which protection options can be judged retrospectively. The distribution of doses that has resulted from

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the implementation of a planned protective strategy may or may not include exposures above the reference level, depending on the success of the strategy. Efforts should, however, be aimed at reducing any exposures that are above the reference level to a level that is below, if possible.

5.9.3. Factors influencing the choice of source-related dose constraints and reference levels

(236) At doses higher than 100 mSv, there is an increased likelihood of deterministic effects and a significant risk of cancer. For these reasons, the Commission considers that the maximum value for a reference level is 100 mSv incurred either acutely or in a year. Exposures above 100 mSv incurred either acutely or in a year would be justified only under extreme circumstances, either because the exposure is unavoidable or in exceptional situations such as the saving of life or the prevention of a serious disaster. No other individual or societal benefit would compensate for such high exposures (see ICRP, 2005a).

(237) Many of the numerical criteria recommended by the Commission in *Publication 60* and subsequent publications can be, with the exception of the limits, regarded as constraints or reference levels. The values fall into three defined bands (see Table 5) with the attributes described in the following paragraphs. The Commission considers that it is useful to present these values in this manner as it enables selection of an appropriate value for a constraint or a reference level for a specific situation that has not been addressed explicitly by the Commission.

(238) The Commission's banding of constraints and reference levels (see Table 5) applies across all three exposure situations and refers to the projected dose over a time period that is appropriate for the situation under consideration. Constraints for planned exposures and reference levels in existing situations are conventionally expressed as an annual effective dose (mSv in a year). In emergency situations the reference level will be expressed as the total residual dose to an individual as a result of the emergency that the regulator would plan not to exceed, either acute (and not expected to be repeated) or, in case of protracted exposure, on an annual basis.

(239) The first band, 1 mSv or less, applies to exposure situations where individuals receive exposures – usually planned – that may be of no direct benefit to them but the exposure situation may be of benefit to society. The exposure of members of the public from the planned operation of practices is a prime example of this type of situation. Constraints and reference levels in this band would be selected for situations where there is general information and environmental surveillance or monitoring or assessment and where individuals may receive information but no training. The corresponding doses would represent a marginal increase above the natural background and are at least two orders of magnitude lower than the maximum value for a reference level, thus providing a rigorous level of protection.

(240) The second band, greater than 1 mSv but not more than 20 mSv, applies in circumstances where individuals receive direct benefits from an exposure situation. Constraints and reference levels in this band will often be set in circumstances where

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Table 5. Framework for source-related dose constraints and reference levels with examples of constraints for workers and the public from single dominant sources for all exposure situations that can be controlled.

Bands of constraints and reference levels[a] (mSv)	**Characteristics of the exposure situation**	**Radiological protection requirements**	**Examples**
Greater than 20 to 100[b,c]	Individuals exposed by sources that are not controllable, or where actions to reduce doses would be disproportionately disruptive. Exposures are usually controlled by action on the exposure pathways.	Consideration should be given to reducing doses. Increasing efforts should be made to reduce doses as they approach 100 mSv. Individuals should receive information on radiation risk and on the actions to reduce doses. Assessment of individual doses should be undertaken.	Reference level set for the highest planned residual dose from a radiological emergency.
Greater than 1 to 20	Individuals will usually receive benefit from the exposure situation but not necessarily from the exposure itself. Exposures may be controlled at source or, alternatively, by action in the exposure pathways.	Where possible, general information should be made available to enable individuals to reduce their doses. For planned situations, individual assessment of exposure and training should take place.	Constraints set for occupational exposure in planned situations. Constraints set for comforters and carers of patients treated with radiopharmaceuticals. Reference level for the highest planned residual dose from radon in dwellings.
1 or less	Individuals are exposed to a source that gives them little or no individual benefit but benefits to society in general. Exposures are usually controlled by action taken directly on the source for which radiological protection requirements can be planned in advance.	General information on the level of exposure should be made available. Periodic checks should be made on the exposure pathways as to the level of exposure.	Constraints set for public exposure in planned situations.

[a] Acute or annual dose.

[b] In exceptional situations, informed volunteer workers may receive doses above this band to save lives, prevent severe radiation-induced health effects, or prevent the development of catastrophic conditions.

[c] Situations in which the dose threshold for deterministic effects in relevant organs or tissues could be exceeded should always require action.

there is individual surveillance or dose monitoring or assessment, and where individuals benefit from training or information. The constraints set for occupational exposure in planned exposure situations are examples. Exposure situations involving

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abnormally high levels of natural background radiation, or stages in post-accident rehabilitation may also be in this band.

(241) The third band, greater than 20 mSv but not more than 100 mSv, applies in unusual, and often extreme, situations where actions taken to reduce exposures would be disruptive. Reference levels and, occasionally for 'one-off' exposures below 50 mSv, constraints could also be set in this range in circumstances where benefits from the exposure situation are commensurately high. Action taken to reduce exposures in a radiological emergency is the main example of this type of situation. The Commission considers that a dose rising towards 100 mSv will almost always justify protective action. In addition, situations in which the dose threshold for deterministic effects in relevant organs or tissues could be exceeded should always require action (see also paragraph 83 in ICRP, 1999a).

(242) A necessary stage in applying the principle of optimisation of protection is the selection of an appropriate value for the dose constraint or the reference level. The first step is to characterise the relevant exposure situation in terms of the nature of the exposure, the benefits from the exposure situation to individuals and society, as well as other societal criteria, and the practicability of reducing or preventing the exposures. Comparison of these attributes with the characteristics described in Table 5 should enable the selection of the appropriate band for the constraint or the reference level. The specific value for the constraint or reference level may then be established by a process of generic optimisation that takes account of national or regional attributes and preferences together, where appropriate, with a consideration of international guidance and good practice elsewhere.

5.10. Dose limits

(243) Dose limits apply only in planned exposure situations but not to medical exposures of patients. The Commission has concluded that the existing dose limits that it recommended in *Publication 60* (ICRP, 1991b) continue to provide an appropriate level of protection. The nominal detriment coefficients for both a workforce and the general public are consistent with, although numerically somewhat lower than, those given in 1990. These slight differences are of no practical significance (see Annex A). Within a category of exposure, occupational or public, dose limits apply to the sum of exposures from sources related to practices that are already justified. The recommended dose limits are summarised in Table 6.

(244) For occupational exposure in planned exposure situations, the Commission continues to recommend that the limit should be expressed as an effective dose of 20 mSv per year, averaged over defined 5 year periods (100 mSv in 5 years), with the further provision that the effective dose should not exceed 50 mSv in any single year.

(245) For public exposure in planned exposure situations, the Commission continues to recommend that the limit should be expressed as an effective dose of 1 mSv in a year. However, in special circumstances a higher value of effective dose could be

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Table 6. Recommended dose limits in planned exposure situations[a].

Type of limit	Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of 5 years[e]	1 mSv in a year[f]
Annual equivalent dose in:		
Lens of the eye[b]	150 mSv	15 mSv
Skin[c,d]	500 mSv	50 mSv
Hands and feet	500 mSv	–

[a] Limits on effective dose are for the sum of the relevant effective doses from external exposure in the specified time period and the committed effective dose from intakes of radionuclides in the same period. For adults, the committed effective dose is computed for a 50-year period after intake, whereas for children it is computed for the period up to age 70 years.

[b] This limit is currently being reviewed by an ICRP Task Group.

[c] The limitation on effective dose provides sufficient protection for the skin against stochastic effects.

[d] Averaged over 1 cm^2 area of skin regardless of the area exposed.

[e] With the further provision that the effective dose should not exceed 50 mSv in any single year. Additional restrictions apply to the occupational exposure of pregnant women.

[f] In special circumstances, a higher value of effective dose could be allowed in a single year, provided that the average over 5 years does not exceed 1 mSv per year.

allowed in a single year, provided that the average over defined 5-year periods does not exceed 1 mSv per year.

(246) The limits on effective dose apply to the sum of doses due to external exposures and committed doses from internal exposures due to intakes of radionuclides. In *Publication 60* (ICRP, 1991b), the Commission stated that occupational intakes may be averaged over a period of 5 years to provide some flexibility. The Commission maintains this view. Similarly, averaging of public intakes over a period of 5 years would be acceptable in such special circumstances where averaging of the dose to members of the public could be allowed (see the previous paragraph).

(247) Dose limits do not apply in emergency exposure situations where an informed, exposed individual is engaged in volunteered life-saving actions or is attempting to prevent a catastrophic situation. For informed volunteers undertaking urgent rescue operations, the normal dose restriction may be relaxed. However, responders undertaking recovery and restoration operations in a later phase of emergency exposure situations should be considered as occupationally exposed workers and should be protected according to normal occupational radiological protection standards, and their exposures should not exceed the occupational dose limits recommended by the Commission. Since the Commission recommends specific protection measures for female workers who have declared that they are pregnant or are nursing an infant (see Section 5.4.1), and taking account of the unavoidable uncertainties surrounding early response measures in the event of an emergency exposure situation, female workers in those conditions should not be employed as first responders undertaking life-saving or other urgent actions.

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(248) For informed individuals of the general public involved in caring and comforting patients released from a hospital following therapy with unsealed radionuclides, the normal dose restriction may be relaxed and such individuals should in general not be subject to the public dose limit (see Section 7.6).

(249) In addition to the limits on effective dose, limits were set in *Publication 60* for the lens of the eye and localised areas of skin because these tissues will not necessarily be protected against tissue reactions by the limit on effective dose. The relevant values were set out in terms of the equivalent dose. These dose limits remain unchanged (see Table 6). However, new data on the radiosensitivity of the eye with regard to visual impairment are expected. The Commission will consider these data and their possible significance for the equivalent dose limit for the lens of the eye when they become available. Because of the uncertainty concerning this risk, there should be particular emphasis on optimisation in situations of exposure of the eyes.

(250) The dose limits for tissues are given in equivalent dose. The reason for this is that the Commission assumes that the relevant RBE values for the deterministic effects are always lower than w_R values for stochastic effects. It is, thus, safely inferred that the dose limits provide at least as much protection against high-LET radiation as against low-LET radiation. The Commission, therefore, believes that it is sufficiently conservative to use w_R with regard to deterministic effects. In special situations where high-LET radiation is the critical factor and where it predominantly exposes a single tissue (such as the skin), it will be more appropriate to express the exposure in terms of the absorbed dose and to take into account the appropriate RBE (see Annex B). To avoid confusion, it is necessary to clearly mention whenever an RBE-weighted absorbed dose in Gy is used.

(251) The Commission's multi-attribute approach to the selection of dose limits necessarily includes societal judgements applied to the many attributes of risk. These judgements would not necessarily be the same in all contexts and, in particular, might be different in different societies. It is for this reason that the Commission intends its guidance to be sufficiently flexible to allow for national or regional variations. In the Commission's view, however, any such variations in the protection of the most highly exposed individuals are best introduced by the use of source-related dose constraints selected by regulatory authorities and applied in the process of optimisation of protection.

5.11. References

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ICRP, 2001a. Doses to the embryo and embryo/fetus from intakes of radionuclides by the mother. ICRP Publication 88. Ann. ICRP 31 (1–3).

ICRP, 2004c. Doses to infants from ingestion of radionuclides in mothers' milk. ICRP Publication 95. Ann. ICRP 34 (3/4).

ICRP, 2005a. Protecting people against radiation exposure in the event of a radiological attack. ICRP Publication 96. Ann. ICRP 35 (1).

ICRP, 2006a. Assessing dose of the representative person for the purpose of radiation protection of the public *and* The optimisation of radiological protection: Broadening the process. ICRP Publication 101. Ann. ICRP 36 (3).

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6. IMPLEMENTATION OF THE COMMISSION'S RECOMMENDATIONS

(252) The previous chapter describes the Commission's system of protection to be applied in all situations requiring a decision on the control of radiation exposures. This chapter addresses the implementation of the system in the three types of exposure situations: planned, emergency, and existing. Particular attention is focused on areas where implementation of the Recommendations may not be immediately straightforward. In a number of these areas, there is further guidance from the Commission as indicated in the text. A section comparing the radiological protection criteria in these Recommendations with those in the previous Recommendations, *Publication 60* (ICRP, 1991b) and derivative publications, is included. The last section of this chapter addresses common aspects of the implementation of the Commission's Recommendations, notably the responsibilities of the users and regulatory authorities.

6.1. Planned exposure situations

(253) Planned exposure situations are where radiological protection can be planned in advance, before exposures occur, and where the magnitude and extent of the exposures can be reasonably predicted. The term encompasses sources and situations that have been appropriately managed within the Commission's previous recommendations for practices. In introducing a planned exposure situation all aspects relevant to radiological protection should be considered. These aspects will include, as appropriate, design, construction, operation, decommissioning, waste management, and rehabilitation of previously occupied land and installations, and will take account of potential exposures as well as normal exposures. Planned exposure situations also include the medical exposure of patients, including their comforters and carers. The principles of protection for planned situations also apply to planned work in connection with existing and emergency exposure situations, once the emergency has been brought under control. Recommendations for planned situations are substantially unchanged from those provided in *Publication 60* (ICRP, 1991b) and subsequent publications for the normal operation of practices and protection in medicine. Because of its specific characteristics, medical exposure is discussed separately in Chapter 7.

(254) All categories of exposure can occur in planned exposure situations, i.e., occupational exposure (Section 6.1.1), public exposure (Section 6.1.2), and medical exposure of patients, including their comforters and carers (Chapter 7). The design and development of planned situations should have proper regard for potential exposures that may result from deviations from normal operating conditions. Due attention should be paid to the assessment of potential exposures and to the related issue of the safety and security of radiation sources (Section 6.1.3).

6.1.1. Occupational exposure

(255) The Commission has previously recommended general principles for the radiological protection of workers (*Publication 75*, ICRP, 1997a). These principles remain valid.

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(256) The Commission continues to recommend that occupational exposure in planned exposure situations be controlled by the procedures of optimisation below a source-related constraint (see Section 5.9.1) and the use of prescriptive dose limits (see Section 5.10). A constraint should be defined at the design stage of a planned exposure situation for its operation. For many types of work in planned exposure situations, it is possible to reach conclusions about the level of individual doses likely to be incurred in well-managed operations. This information can then be used to establish a dose constraint for that type of work. This work should be specified in fairly broad terms, such as work in industrial radiography, the routine operation of nuclear power plants, or work in medical establishments. However, there may also be more specific situations where a constraint can be established to guide particular activities.

(257) It will usually be appropriate for such dose constraints to be set at the operational level. When using a dose constraint, a designer should specify the sources to which the constraint is linked so as to avoid confusion with other sources to which the workforce might be concurrently exposed. The source-related dose constraint for occupational exposure in planned situations should be set to ensure that the dose limit is not exceeded (see Section 5.10). Experience gained in managing workers exposed to radiation will inform the choice of a value for a constraint for occupational exposure. For this reason, large established organisations, having a comprehensive radiological protection infrastructure, will often set their own constraints for occupational exposure. Smaller organisations with less relevant experience may require further guidance on this topic from the appropriate expert bodies or regulatory authorities. Nevertheless, the overall responsibility for setting constraints lies with those who are responsible for worker exposure.

(258) Protection of transient or itinerant workers requires particular attention because of the potential shared responsibility of several employers and licensees. In addition, sometimes several regulatory authorities are involved. Such workers include contractors for maintenance operations in nuclear power plants and industrial radiographers, who are not on the staff of the operator. In order to provide for their protection, adequate consideration needs to be given to the previous exposures of these workers so as to ensure that dose limits are also respected, and their exposure should be followed up. Thus there should be an adequate degree of co-operation between the employer of the itinerant worker and the operators of the plants for whom contracts are being undertaken. Regulatory authorities should ensure that regulations are adequate in this respect.

6.1.2. Public exposure

(259) In planned exposure situations, the Commission continues to recommend that public exposure be controlled by the procedures of optimisation below the source-related constraint and by the use of dose limits. In general, especially for public exposure, each source will cause a distribution of doses over many individuals, so the concept of a *Representative Person* should be used to represent the more highly exposed individuals (ICRP, 2006a). Constraints for members of the public in

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planned exposure situations should be smaller than public dose limits, and would typically be set by the national regulatory authorities.

(260) For the control of public exposure from waste disposal, the Commission has previously recommended that a value for the dose constraint for members of the public of no more than about 0.3 mSv in a year would be appropriate (ICRP, 1997d). These Recommendations were further elaborated for the planned disposal of long-lived radioactive waste in *Publication 81* (ICRP, 1998b).

(261) In *Publication 82* (ICRP, 1999a), the Commission issued guidance that in circumstances where there are planned discharges of long-lived radionuclides to the environment, planning assessments should consider whether build-up in the environment would result in the constraint being exceeded, taking account of any reasonable combination and build-up of exposures. Where such verification considerations are not possible or are too uncertain, it would be prudent to apply a dose constraint of the order of 0.1 mSv in a year to the prolonged component of the dose attributable to the long-lived artificial radionuclides. In planned exposure situations involving natural radioactive material, this limitation is not feasible and not required (ICRP, 1999a). These Recommendations remain valid. In order to ensure that the build-up of annual doses from continuing practices does not cause dose limits to be exceeded in the future, the dose commitment can be used (ICRP, 1991b, IAEA, 2000b). This is the total dose that would eventually result from an event, such as a year of a planned activity causing discharges. Some flexibility may be required for particular situations involving long-lived natural radionuclides, such as past mining and milling activities (see Sections 2.3 and 5.2.2 of *Publication 82*, ICRP, 1999a).

6.1.3. Potential exposures

(262) In planned exposure situations, a certain level of exposure is reasonably expected to occur. However, higher exposures may arise following deviations from planned operating procedures, accidents including the loss of control of radiation sources, and malevolent events. Such exposures are not planned to occur, although the situation is planned. These exposures are referred to by the Commission as *potential exposures*. Deviations from planned operating procedures and accidents can often be foreseen and their probability of occurrence estimated, but they cannot be predicted in detail. Loss of control of radiation sources and malevolent events are less predictable and call for a specific approach.

(263) There is usually an interaction between potential exposures and the exposures arising from planned operations in normal operation; for example, actions taken to reduce the exposure during normal operations may increase the probability of potential exposures. Thus, the storage of long-lived waste rather than its dispersal could reduce the exposures from discharges but would increase potential exposures. In order to control potential exposure, certain surveillance and maintenance activities will be undertaken. These activities may increase normal exposures.

(264) Potential exposures should be considered at the planning stage of the introduction of a planned exposure situation. It should be recognised that the potential

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for exposures may lead to actions both to reduce the probability of the events occurring, and to limit and reduce the exposure (mitigation) if any event were to occur (ICRP, 1991b, 1997b). Due consideration should be afforded to potential exposures during application of the principles of justification and optimisation.

(265) Potential exposure broadly covers three types of events.

- Events where the potential exposures would primarily affect individuals who are also subject to planned exposures: The number of individuals is usually small, and the detriment involved is the health risk to the directly exposed persons. The processes by which such exposures occur are relatively simple, e.g., the potential unsafe entry into an irradiation room. The Commission has given specific guidance for the protection from potential exposures in such circumstances in *Publication 76* (ICRP, 1997b). This guidance remains valid. Some additional examples are discussed in Section 7.5 on accidents in medical contexts.
- Events where the potential exposures could affect a larger number of people and not only involve health risks but also other detriments, such as contaminated land and the need to control food consumption: The mechanisms involved are complicated and an example is the potential for a major accident in a nuclear reactor or the malicious use of radioactive material. The Commission has provided a conceptual framework for the protection from such type of events in *Publication 64* (ICRP, 1993a). This framework remains valid. In *Publication 96* (ICRP, 2005a), the Commission provides some additional advice concerning radiological protection after events involving malicious intent.
- Events in which the potential exposures could occur far in the future, and the doses be delivered over long time periods, e.g., in the case of solid waste disposal in deep repositories: Considerable uncertainties surround exposures taking place in the far future. Thus dose estimates should not be regarded as measures of health detriment beyond times of around several hundreds of years into the future. Rather, they represent indicators of the protection afforded by the disposal system. The Commission has given specific guidance for the disposal of long-lived solid radioactive waste in *Publication 81* (ICRP, 1998b). This guidance remains valid.

Assessment of potential exposures

(266) The evaluation of potential exposures, for the purpose of planning or judging protection measures, is usually based on: a) the construction of scenarios which are intended typically to represent the sequence of events leading to the exposures; b) the assessment of probabilities of each of these sequences; c) the assessment of the resulting dose; d) the evaluation of detriment associated with that dose; e) comparison of the results with some criterion of acceptability; and f) optimisation of protection which may require several iterations of the previous steps.

(267) The principles of constructing and analysing scenarios are well known and are often used in engineering. Their application was discussed in *Publication 76* (ICRP, 1997b). Decisions on the acceptability of potential exposures should take account of both the probability of occurrence of the exposure and its magnitude. In some circumstances, decisions can be made by separate consideration of these

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two factors. In other circumstances, it is useful to consider the individual probability of radiation-related death, rather than the effective dose (ICRP, 1997b). For this purpose, the probability is defined as the product of the probability of incurring the dose in a year and the lifetime probability of radiation-related death from the dose conditional on the dose being incurred. The resulting probability can then be compared with a risk constraint. If the probability is lower than the risk constraint, it may be tolerated. Both of these approaches are discussed in the Commission's Recommendations for the disposal of long-lived solid radioactive waste in *Publication 81* (ICRP, 1998b).

(268) Risk constraints, like dose constraints, are source-related and in principle should equate to a similar health risk to that implied by the corresponding dose constraints for the same source. However, there can be large uncertainties in estimations of the probability of an unsafe situation and the resulting dose. Thus, it will often be sufficient to use a generic value for a risk constraint. In the case of workers, this could be based on generalisations about normal occupational exposures, rather than on a more specific study of the particular operation. Where the Commission's system of dose limitation has been applied and protection is optimised, annual occupational effective doses to an average individual may be as high as about 5 mSv in certain selected types of operation (UNSCEAR, 2000). For potential exposures of workers, the Commission therefore continues to recommend a generic risk constraint of $2\ 10^{-4}$ per year which is similar to the probability of fatal cancer associated with an average occupational annual dose of 5 mSv (ICRP, 1997b). For potential exposures of the public, the Commission continues to recommend a risk constraint of $1\ 10^{-5}$ per year.

(269) The use of probability assessment is limited by the extent that unlikely events can be forecast. In circumstances where accidents can occur as a result of a wide spectrum of initiating events, caution should be exercised over any estimate of overall probabilities because of the serious uncertainty of predicting the existence of all the unlikely initiating events. In many circumstances, more information can be obtained for decision-making purposes by considering the probability of occurrence and the resultant doses separately.

(270) In large nuclear installations, dose criteria as a design basis of accident prevention and mitigation may be prescribed by the regulatory agency for selected potential exposure scenarios. The dose criteria applied here for the potential exposure should be derived from the risk constraints by taking account of the probability of the accident.

Safety and security of radiation sources and malevolent events

(271) Potential exposures associated with planned exposure situations may result from the loss of control of radiation sources. This situation has received a growing attention over recent years and deserves a special consideration from the Commission. The Recommendations of the Commission presume that, as a precondition for adequate radiological protection, radiation sources are subject to proper security measures (ICRP, 1991b). The control of radiation exposure in all planned exposure situations is exercised by the application of controls at the source rather than in the

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environment. The Commission's view is reflected in the International Basic Safety Standards (BSS), which require that the control of sources shall not be relinquished under any circumstances (IAEA, 1996). The BSS also requires that sources be kept secure so as to prevent theft or damage. In addition, the Code of Conduct on the Safety and Security of Radioactive Sources establishes basic principles applicable to the security of radioactive sources (IAEA, 2004). The Commission supports the global strengthening of the control of radiation sources.

(272) Security of radioactive sources is a necessary, but not sufficient, condition to ensure source safety. Radioactive sources can be secure, i.e., under proper control, for instance preventing malicious use of the sources, and still not safe, i.e., prone to accidents. Thus the Commission has historically included aspects of security in its system of protection (ICRP, 1991b). In the context of safety, security provisions are generally limited to general controls necessary to prevent loss, access, unauthorised possession or transfer and use of the material, devices or installations. Measures to ensure that the control of radioactive material and access to radiation devices and installations are not relinquished are also essential to maintain safety.

(273) The Commission's 1990 Recommendations did not give attention to measures specifically to protect against terrorism or other malicious acts. However, it has become evident that radiation safety must also include the potential for such scenarios. Past experience with unintentional breaches in source security, or where a discarded or orphan source was found by individuals unaware of the radiation hazard, indicates what might occur if radioactive materials are used intentionally to cause harm, e.g., by deliberate dispersion of radioactive material in a public area. Such events have the potential for exposing people to radiation and causing significant environmental contamination, which would require specific radiological protection measures (ICRP, 2005a).

6.2. Emergency exposure situations

(274) Even if all reasonable steps have been taken during the design stage to reduce the probability and consequences of potential exposures, such exposures may need to be considered in relation to emergency preparedness and response. Emergency exposure situations are unexpected situations that may require urgent protective actions, and perhaps also longer-term protective actions, to be implemented. Exposure of members of the public or of workers, as well as environmental contamination can occur in these situations. Exposures can be complex in the sense that they may result from several independent pathways, perhaps acting simultaneously. Furthermore, radiological hazards may be accompanied by other hazards (chemical, physical, etc.). Response actions should be planned because potential emergency exposure situations can be assessed in advance, to a greater or lesser accuracy depending upon the type of installation or situation being considered. However, because actual emergency exposure situations are inherently unpredictable, the exact nature of necessary protection measures cannot be known in advance but must flexibly evolve to meet actual circumstances. The complexity and variability of these situations give them

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a unique character that merits their specific treatment by the Commission in its Recommendations.

(275) The Commission has set out general principles for planning intervention in the case of a radiation emergency in *Publications 60* and *63* (ICRP, 1991b, 1992). Additional relevant advice is given in *Publications 86, 96, 97,* and *98* (ICRP, 2000c, 2005a, 2005b, 2005c). While the general principles and additional advice remain valid, the Commission is now extending its guidance on the application of protective measures on the basis of recent developments in emergency preparedness and of experience since publication of its previous advice.

(276) The Commission now emphasises the importance of justifying and optimising protection strategies for application in emergency exposure situations, the optimisation process being guided by reference levels (see Section 5.9). The possibility of multiple, independent, simultaneous, and time-varying exposure pathways makes it important to focus on the overall exposures that may occur from all pathways when developing and implementing protective measures. As such, an overall protection strategy is necessary, generally including an assessment of the radiological situation and implementation of different protective measures. These measures may well vary with time, as the emergency exposure situation evolves, and with place, as the emergency exposure situation may affect distinct geographic areas differently. The overall exposure, which is projected to occur as a result of the emergency exposure situation, should no protective actions be employed, is called the *projected dose*. The dose that would result when a protection strategy is implemented is called the *residual dose*. In addition, each protective measure will avert a certain amount of exposure. This is referred to as *averted dose*, and is the concept for the optimisation of the individual protective measures as given in *Publication 63* (ICRP, 1992) that will make up the overall protection strategy. The Commission now recommends focusing on optimisation with respect to the overall strategy, rather than the individual measures. However, the levels of averted dose recommended in *Publication 63* for optimisation of protection in terms of individual protective measures may still be useful as inputs to the development of the overall response (see also *Publication 96*, ICRP, 2005a).

(277) In emergency exposure situations particular attention should be given to the prevention of severe deterministic health effects as doses could reach high levels in a short period of time. In case of major emergencies an assessment based on health effects would be insufficient and due considerations must be given to societal, economic and other consequences. Another important objective is to prepare, to the extent practicable, for the resumption of societal and economic activities considered as 'normal'.

(278) In planning for emergency situations, reference levels should be applied in the process of optimisation. Reference levels for the highest planned residual doses in emergency situations are typically in the 20 mSv to 100 mSv band of projected dose as presented in Section 5.9.3. Expected residual doses for the overall protection strategies are compared with the reference levels in initially assessing the suitability of the strategies. A protection strategy that would not reduce residual doses to below the reference levels should be rejected at the planning stage.

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(279) Planning should result in a set of actions that would be implemented automatically once an emergency exposure situation has occurred, should the actual circumstances require such urgent actions. Following a decision on such immediate action, the projected residual dose distribution can be assessed, and the reference level acts as a benchmark for assessing the effectiveness of protection strategies and the need to modify or take additional actions. All exposures above or below the reference level should be subject to optimisation of protection, and particular attention should be given to exposures above the reference level.

(280) When preparing a protection strategy for a particular emergency exposure situation, a number of different populations, each needing specific protective measures, may be identified. For example, the distance from the origin of an emergency exposure situation (e.g., an installation, an emergency site) may be important in terms of identifying the magnitude of exposures to be considered, and thus the types and urgency of protective measures. With this diversity of exposed populations in mind, the planning of protective measures should be based on exposures to the Representative Persons, as described in *Publication 101* (ICRP, 2006a), from the various populations that have been identified. After an emergency situation has occurred, planned protection measures should evolve to best address the actual conditions of all exposed populations being considered. Particular attention should be given to pregnant women and children.

(281) Emergency plans should be developed (in more or less detail, as appropriate) to cope with all possible scenarios. The development of an emergency plan (national, local, or installation specific) is a multi-step iterative process that includes assessment, planning, resource allocation, training, exercises, audit, and revision. The radiation emergency response plans should be integrated into all-hazards emergency management programmes.

(282) In the event that an emergency exposure situation occurs, the first issue is to recognise its onset. The initial response should be to follow the emergency plan in a consistent but flexible way. The protection strategy initially implemented will be that described in the emergency plan for the relevant event scenario, based on the generic optimisation undertaken as part of the planning stage. Once the measures in the emergency plan have been initiated, emergency response can be characterised by an iterative cycle of review, planning, and execution.

(283) Emergency response is inevitably a process that develops in time from a situation of little information to one of potentially overwhelming information, with the expectations for protection and involvement by those affected similarly increasing rapidly with time. As discussed in *Publication 96* (ICRP, 2005a), three phases of an emergency exposure situation are considered: the early phase (which may be divided into a warning and possible release phase), the intermediate phase (which starts with the cessation of any release and regaining control of the source of releases), and the late phase. At any stage, decision-makers will necessarily have an incomplete understanding of the situation regarding the future impact, the effectiveness of protective measures, and the concerns of those directly and indirectly affected, amongst other factors. An effective response must therefore be developed flexibly with regular review of its impact. The reference level provides an important

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input to this review, providing a benchmark against which what is known about the situation and the protection afforded by implemented measures can be compared. The management of long-term contamination resulting from an emergency situation is treated as an existing exposure situation (see Section 6.3).

6.3. Existing exposure situations

(284) Existing exposure situations are those that already exist when a decision on control has to be taken. There are many types of existing exposure situations that may cause exposures high enough to warrant radiological protective actions, or at least their consideration. Radon in dwellings or the workplace, and naturally occurring radioactive material (NORM) are well-known examples. It may also be necessary to take radiological protection decisions concerning existing man-made exposure situations such as residues in the environment resulting from radiological emissions from operations that were not conducted within the Commission's system of protection, or contaminated land resulting from an accident or a radiological event. There are also existing exposure situations for which it will be obvious that action to reduce exposures is not warranted. The decision as to what components of existing exposure are not amenable to control requires a judgement by the regulatory authority that will depend on the controllability of the source or exposure, and also on the prevailing economic, societal, and cultural circumstances. Principles for exclusion and exemption of radiation sources are presented and discussed in Section 2.3.

(285) Existing exposure situations can be complex in that they may involve several exposure pathways and they generally give rise to wide distributions of annual individual doses ranging from the very low to, in rare cases, several tens of millisieverts. Such situations often involve dwellings, for example in the case of radon, and in many cases the behaviour of the exposed individuals determines the level of exposure. Another example is the distribution of individual exposures in a long-term contaminated territory, which directly reflects differences in the dietary habits of the affected inhabitants. The multiplicity of exposure pathways and the importance of individual behaviour may result in exposure situations that are difficult to control.

(286) The Commission recommends that reference levels, set in terms of individual dose, should be used in conjunction with the implementation of the optimisation process for exposures in existing exposure situations. The objective is to implement optimised protection strategies, or a progressive range of such strategies, which will reduce individual doses to below the reference level. However, exposures below the reference level should not be ignored; these exposure circumstances should also be assessed to ascertain whether protection is optimised, or whether further protective measures are needed. An endpoint for the optimisation process must not be fixed a priori and the optimised level of protection will depend on the situation. It is the responsibility of regulatory authorities to decide on the legal status of the reference level, which is implemented to control a given situation. Retrospectively, when protective actions have been implemented, reference levels may also be used as benchmarks for assessing the effectiveness of the protection strategies. The use of

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reference levels in an existing situation is illustrated in Fig. 4, which shows the evolution of the distribution of individual doses with time as a result of the optimisation process.

(287) Reference levels for existing exposure situations should be set typically in the 1 mSv to 20 mSv band of projected dose as presented in Sections 5.9.2 and 5.9.3 and Table 5. The individuals concerned should receive general information on the exposure situation and the means of reducing their doses. In situations where individual life-styles are key drivers of the exposures, individual monitoring or assessment as well as education and training may be important requirements. Living on contaminated land after a nuclear accident or a radiological event is a typical situation of that sort.

(288) The main factors to be considered for setting the reference levels for existing exposure situations are the feasibility of controlling the situation, and the past experience with the management of similar situations. In most existing exposure situations, there is a desire from the exposed individual, as well as from the authorities, to reduce exposures to levels that are close to or similar to situations considered as 'normal'. This applies particularly in situations of exposures from material resulting from human actions, e.g., NORM residues and contamination from accidents.

6.3.1. Indoor radon in dwellings and workplaces

(289) Exposure to radon in dwellings and workplaces may arise from existing exposure situations or from practices, e.g., storage or processing of monazite sands. The Commission has previously made specific recommendations in relation to radon exposure (ICRP, 1993b). Since then, several epidemiological studies have confirmed the risk of radon-222 exposure even at relatively moderate concentrations (UNSCEAR, 2008). European, North American, and Chinese residential case-control studies also demonstrate a significant association between the risk of lung cancer and exposure to residential radon-222 (Darby et al., 2006, Krewski et al., 2006, Lubin et al., 2004). These studies have generally provided support for the Commission's Recommendations on protection against radon.

(290) There is now a remarkable coherence between the risk estimates developed from epidemiological studies of miners and residential case-control radon studies. While the miner studies provide a strong basis for evaluating risks from radon exposure and for investigating the effects of modifiers to the dose–response relation, the results of the recent pooled residential studies now provide a direct method of estimating risks to people at home without the need for extrapolation from miner studies (UNSCEAR, 2008).

(291) The Commission's view on radon risk assessment has, until now, been that it should incorporate epidemiological studies of miners. Given the wealth of data now available on domestic exposure to radon, the Commission recommends that the estimation of risk from domestic radon exposure should include the results of pooled residential case control radon-222 studies. However, there is still great value in the miner epidemiology studies for investigating dose response relationships and confounding effects of smoking and exposure to other agents. The currently available

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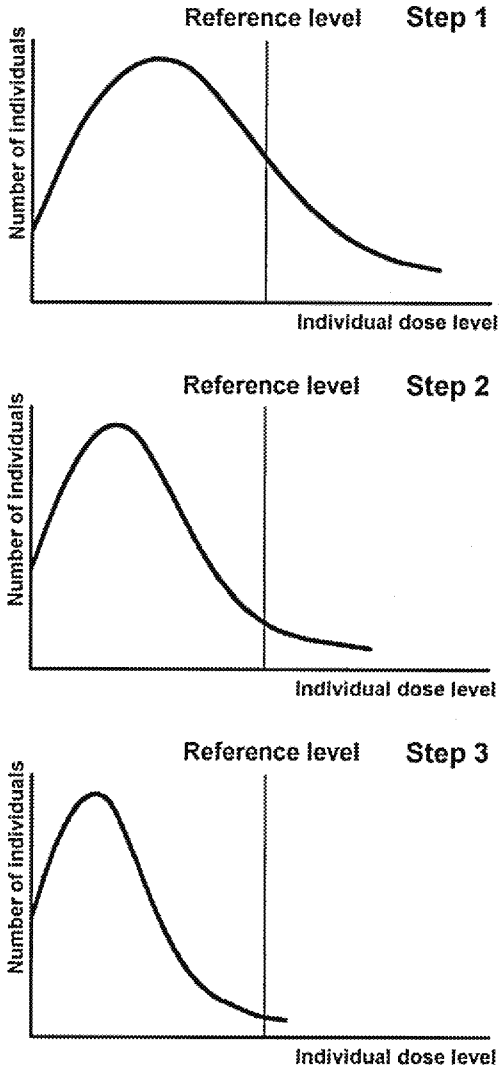

Fig. 4. The use of a reference level in an existing exposure situation and the evolution of the distribution of individual doses with time as a result of the optimisation process.

epidemiological evidence indicates that risks other than lung cancer from exposure to radon-222 (and decay products) are likely to be small.

(292) The underlying theme of the Commission's Recommendations on radon is the controllability of exposure. The ability to control exposure distinguishes the circumstances under which exposure to radon in workplaces, including underground mines, may need to be subject to the Commission's system of protection and where the need for action to limit radon exposure in dwellings should be considered. There

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are several reasons for treating radon-222 in this separate manner. The exposure route differs from that of other natural sources, and there are dosimetric and epidemiological issues specific to radon-222. For many individuals radon-222 is an important source of exposure which, in principle, can be controlled. The Commission issued the current recommendations for protection against radon-222 at home and at work in *Publication 65* (ICRP, 1993b). The policy has found wide acceptance and the present Recommendations broadly continue the same policy, with an adaptation to the new approach based on exposure situations and where a central role is given to the optimisation principle and the use of reference levels.

(293) In *Publication 65* (ICRP, 1993b), the policy was based upon first setting a level to an effective dose of 10 mSv per year from radon-222 where action would almost certainly be warranted to reduce the exposure. Regulatory authorities were expected to apply the optimisation of protection in a generic way to find a lower level at which to act, in the range from 3 to 10 mSv. The effective dose was converted by a dose conversion convention into a value of radon-222 concentration, which was different between homes and workplaces largely because of the different number of hours spent at each. For dwellings this range was a radon concentration of 200–600 Bq m^{-3}, while the corresponding range for workplaces was 500–1500 Bq m^{-3}. The result of the optimisation was to set action levels, i.e., levels above which action was required to reduce the dose.

(294) The Commission now recommends applying the source-related principles of radiological protection for controlling radon exposure. This means that national authorities need to set national reference levels to aid the optimisation of protection. Even though the nominal risk per Sv has changed slightly, the Commission, for the sake of continuity and practicality, retains the upper value of 10 mSv for the individual dose reference level, and the corresponding activity concentrations as given in *Publication 65* (ICRP, 1993b). Thus, the upper values for the reference level expressed in activity concentrations remain at 1500 Bq m^{-3} for workplaces and 600 Bq m^{-3} for homes (Table 7).

(295) It is the responsibility of the appropriate national authorities, as with other sources, to establish their own national reference levels, taking into account the prevailing economic and societal circumstances and then to apply the process of optimisation of protection in their country. All reasonable efforts should be made to reduce radon-222 exposures in homes and at work places to below the reference levels that are set at the national level and to a level where protection can be considered optimised. The actions taken should be intended to produce substantial reduction in radon exposures. It is not sufficient to adopt marginal improvements aimed only

Table 7. Reference levels for radon-222[†].

Situation	Upper value of reference level: Activity concentration
Domestic dwellings	600 Bq m^{-3}
Workplaces	1500 Bq m^{-3}

[†] Head or initial radionuclide of the decay chain activity level.

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at reducing the radon concentrations to a value just below the national reference level.

(296) The implementation of the optimisation process should result in concentration activities below the national reference levels. In general, no further action will be required apart from perhaps monitoring activity concentration sporadically to ensure that levels remain low. National authorities should, however, periodically review the values of the national reference levels for radon exposure to ensure that they remain appropriate.

(297) Responsibility for taking action against radon in houses and other premises will often fall on the individual owners, who cannot be expected to carry out a detailed optimisation exercise for each property. Therefore, in addition to reference levels, regulatory authorities may also wish to specify levels at which protection against radon-222 can be considered optimised, i.e., where no further action is needed. The Commission's view continues to be that there is merit in defining radon-prone areas in which the concentration of radon in buildings is likely to be higher than is typical of the country as a whole. This allows attention to be focused on radon where it is most exigent and action to be concentrated where it is most likely to be effective (ICRP, 1993b).

(298) Radon exposure at work at levels above the national reference level should be considered part of occupational exposure whereas exposures at levels below should not. In the interest of international harmonisation of occupational safety standards, a single action level value of 1000 Bq m^{-3} was established in the BSS (IAEA, 1996). For the same reasons, the Commission considers that this internationally established value, which is a reference value in current terminology, might be used globally to define the entry point for occupational protection requirements for exposure situations to radon. In fact, this international level serves as a much needed globally harmonised monitoring and record-keeping system. This is relevant for determining when the occupational radiological protection requirements apply – i.e., what is actually included within the system of regulatory control. On this basis the BSS establishes limits on intake and exposures for radon and thoron progeny (see Table II.1 in IAEA, 1996).

6.4. Protection of the embryo/fetus in emergency and existing exposure situation

(299) In *Publication 82* (ICRP, 1999a), the Commission concluded that prenatal exposure would not be a specific protection case, i.e., would not require protective actions other than those aimed at the general population. The protection of the embryo/fetus and infants is discussed in Section 5.4.1. In *Publication 82* (ICRP, 1999a), the Commission provided practical recommendations concerning in-utero exposures. Dose coefficients for the embryo/fetus due to intakes of radionuclides by the mother were provided in *Publication 88* (ICRP, 2001a). The Commission's conclusion in *Publication 90* (ICRP, 2003a) was that newly available information on in-utero risk at low doses (up to a few tens of mSv) supported the advice developed in *Publications 60*, *82*, *84*, and *88* (ICRP 1991b, 1999a, 2000a, 2001a). The Commission position on these issues remains unchanged.

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6.5. Comparison of radiological protection criteria

(300) The current recommended values for protection criteria are compared in Table 8 with those provided by the previous Recommendations in *Publication 60* (ICRP, 1991b) and the derivative publications. The comparison shows that the current Recommendations are essentially the same as the previous Recommendations for planned exposure situations. In the case of existing and emergency exposure situations, the current Recommendations generally encompass the previous values but are wider in their scope of application. It should be noted that in some cases the values cited are in different quantities; for example, in emergency exposure situ-

Table 8. Comparison of protection criteria between the 1990 and the 2007 Recommendations (numbers in brackets refer to ICRP Publication numbers; ICRP, 1991b,c, 1992, 1993b, 1994b, 1997a,d, 1998b, 1999a, 2004b, 2005a,c).

Categories of exposure (Publications)	1990 Recommendations and subsequent publicatious	Present Recommendations
Planned exposure situations		
	Individual dose limits[a]	
Occupational exposure (60, 68, 75) including recovery operations (96)	20 mSv/year average over defined periods of 5 years[c]	20 mSv/year average over defined periods of 5 years[c]
– lens of the eye	150 mSv/year[b]	150 mSv/year[b]
– skin	500 mSv/year[b]	500 mSv/year[b]
– hands and feet	500 mSv/year[b]	500 mSv/year[b]
– pregnant women, remainder of pregnancy	2 mSv to the surface of abdomen or 1 mSv from intake of radionuclides	1 mSv to the embryo/fetus
Public exposure (60)	1 mSv in a year	1 mSv in a year
– lens of the eye	15 mSv/year[b]	15 mSv/year[b]
– skin	50 mSv/year[b]	50 mSv/year[b]
	Dose constraints[a]	
Occupational exposure (60)	⩽20 mSv/year	⩽20 mSv/year
Public exposure (77, 81, 82)		To be selected below 1 mSv/year according to the situation
– general	–	
– radioactive waste disposal	⩽0.3 mSv/year	⩽0.3 mSv/year
– long-lived radioactive waste disposal	⩽0.3 mSv/year	⩽0.3 mSv/year
– prolonged exposure	< ~ 1 & ~0.3 mSv/year[f]	<~1 & ~0.3 mSv/year[f]
– prolonged component from long-lived nuclides	⩽0.1 mSv/year[h]	⩽0.1 mSv/year[h]
Medical exposure (62, 94, 98)		
– volunteers for biomedical research, if benefit to society is:		
– minor	< 0.1 mSv	< 0.1 mSv
– intermediate	0.1–1 mSv	0.1–1 mSv
– moderate	1–10 mSv	1–10 mSv
– substantial	> 10 mSv	> 10 mSv
– comforters and carers	5 mSv per episode	5 mSv per episode

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Table 8 (*continued*)

Categories of exposure (Publications)	1990 Recommendations and subsequent publications	Present Recommendations
Emergency exposure situations		
	Intervention levels[a,d,g]	**Reference levels**[a,g]
Occupational exposure (60, 96)		
– life-saving (informed volunteers)	No dose restrictions[i]	No dose restrictions if benefit to others outweighs rescuer's risk[k]
– other urgent rescue operations	~500 mSv; ~5 Sv (skin)[i]	1000 or 500 mSv[k]
– other rescue operations	...	⩽100 mSv[k]
Public exposure (63, 96) ***Public exposure:***		
– foodstuffs	10 mSv/year[l]	
– distribution of stable iodine	50–500 mSv (thyroid) [b,l]	
– sheltering	5–50 mSv in 2 days[l]	
– temporary evacuation	50–500 mSv in 1 week[l]	
– permanent relocation	100 mSv first year or 1000 mSv[l]	
– all countermeasures combined in an overall protection strategy	...	In planning, typically between 20 and 100 mSv/year according to the situation[e]
Existing exposure situations		
	Action levels[a]	**Reference levels**[a,m]
Radon (65)		
– at home	3–10 mSv/year (200–600 Bq m^{-3})	<10 mSv/year (<600 Bq m^{-3})
– at work	3–10 mSv/year (500–1500 Bq m^{-3})	<10 mSv/year (<1500 Bq m^{-3})
	Generic reference levels[e]	**Reference levels**[c,m]
NORM, natural background radiation, radioactive residues in human habitat (82)		
Interventions:		
– unlikely to be justifiable	< ~ 10 mSv/year	Between 1 and 20 mSv/year
– may be justifiable	> ~ 10 mSv/year	according to the situation
– almost always justifiable	towards 100 mSv/year	(See Section 5.9.2)

[a] Effective dose unless otherwise specified.

[b] Equivalent dose.

[c] With the further provision that the effective dose should not exceed 50 mSv in any one year. Additional restrictions apply to the occupational exposure of pregnant women. When applied to the intake of radionuclides, the dose quantity is committed effective dose.

[d] Averted dose.

[e] See Sections 5.9 and 6.2.

[f] The dose constraint should be less than 1 mSv and a value of no more than about 0.3 mSv would be appropriate.

[g] Intervention Levels refer to averted dose for specific countermeasures. Intervention Levels remain valuable for optimisation of individual countermeasures when planning a protection strategy, as a supplement to Reference Levels for evaluation of protection strategies; these refer to residual dose.

[h] To be considered if dose assessment methodologies to ensure compliance under any conceivable situation of combination of doses is not available.

[i] *Publication 60* (ICRP, 1991b).

[k] *Publication 96* (ICRP, 2005a). Effective doses below 1000 mSv should avoid serious deterministic effects; below 500 mSv should avoid other deterministic effects.

[l] *Publication 63* (ICRP, 1992).

[m] Reference Levels refer to residual dose and are used to evaluate protection strategies, as opposed to the previously recommended Intervention Levels which referred to averted doses from individual protective actions.

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ations the criteria in *Publication 60* (ICRP, 1991b) are specified in terms of averted dose (intervention levels) whereas the criteria in the current Recommendations are specified in terms of incremental dose (reference levels). These differences are noted in Table 8.

6.6. Practical implementation

(301) This section addresses the general implementation of the Commission's Recommendations, dealing with factors which are common to the three types of exposure situations. It focuses on organisational features that may help in the implementation of the Commission's Recommendations. Since the organisational structures will differ from country to country, the chapter is illustrative rather than exhaustive. The International Atomic Energy Agency and the Nuclear Energy Agency of OECD issue further advice on the infrastructure required for radiological protection in various circumstances to their member states (e.g., see IAEA, 1996, 2000a, 2002, and NEA, 2005). Generic advice on organisation for health and safety at work is provided by the International Labour Organization, the World Health Organization and the Pan-American Health Organization.

6.6.1. The infrastructure for radiological protection and safety

(302) An infrastructure is required to ensure that an appropriate standard of protection is maintained. This infrastructure includes at least a legal framework, a regulatory authority, the operating management of any undertaking involving ionising radiation (including the design, operation, and decommissioning of equipment and installations as well as adventitious enhancement of natural radiation including aviation and space flight), and the employees at such undertakings. It may include additional organisations and persons responsible for protection and safety.

(303) The legal framework must provide for the regulation, as required, of undertakings involving ionising radiation and for the clear assignment of responsibilities for protection and safety. A regulatory authority must be responsible for the regulatory control, whenever required, of undertakings involving radiation and for the enforcement of the regulations. This regulatory authority must be clearly separate from organisations that conduct or promote activities causing radiation exposure.

(304) The nature of radiological hazards necessitates a number of special features in the legal framework and the provision of expertise within the regulatory authority. The important issues are that radiological questions are addressed properly, that the appropriate expertise is available, and that decisions concerning radiation safety cannot be unduly influenced by economic or other non-radiological considerations.

(305) The primary responsibility for achieving and maintaining a satisfactory control of radiation exposures rests on the management bodies of the institutions conducting the operations giving rise to the exposures. When equipment or plant is designed and supplied by other institutions, they, in turn, have a responsibility to

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see that the items supplied will be satisfactory, if used as intended. Governments have the responsibility to set up national authorities, which then have the responsibility for providing a regulatory, and often also an advisory, framework to emphasise the responsibilities of the management bodies while, at the same time, setting and enforcing overall standards of protection. They may also have to take direct responsibility when, as with exposures to many natural sources, there is no relevant management body.

(306) There are various reasons why there may not be a relevant operating management available. For instance, the radiation may not have been caused by any human actions, or an activity may have been abandoned and the proprietors could have disappeared. In such cases, the national regulatory authority, or some other designated body, will have to accept some of the responsibilities usually carried by the operating management.

(307) In all organisations, the responsibilities and the associated authority are delegated to an extent depending on the complexity of the duties involved. The working of this delegation should be examined regularly. However, the management of the organisation remains accountable for the provision of adequate radiological protection, and the delegation of tasks and responsibilities does not detract from that accountability. There should be a clear line of accountability running right to the top of each organisation. There is also an interaction between the various kinds of organisation. Advisory and regulatory authorities should be held accountable for the advice they give and any requirements they impose.

(308) Requirements, operating instructions, regulatory approvals and licences, and other administrative devices are not, of themselves, enough to achieve an appropriate standard of radiological protection. Everyone in an activity, from the individual workers and their representatives to the senior management, should regard protection and emergency prevention as integral parts of their everyday functions. Success and failure in these areas are at least as important as they are in the primary function of the activity.

(309) The imposition of requirements expressed in general terms and the acceptance of advice do not reduce the responsibility, or the accountability, of the operating organisations. This is also true in principle of prescriptive requirements, where the regulatory authority prescribes in detail how protection standards are to be maintained. However, prescriptive requirements concerning the conduct of operations result in some de facto transfer of responsibility and accountability from the user to the regulatory authority. In the long run, they also reduce the user's incentive for self-improvement. Therefore, it is usually better to adopt a regulatory regime that places a more explicit responsibility on the user, and forces the user to convince the regulatory authority that adequate protection methods and standards are used and maintained.

(310) Therefore, the use of prescriptive requirements should always be carefully justified. In any event, they should never be regarded as an alternative to the process of optimising protection. It is not satisfactory to set design or operational limits or targets as an arbitrary fraction of the dose limit, regardless of the particular nature of the plant and the operations.

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6.6.2. External expertise and advice; delegation of authority

(311) The prime responsibility for radiological protection and radiation safety in an undertaking involving ionising radiation rests with the operating organisation. In order to assume this responsibility, the organisation needs expertise in radiological protection. It is not always necessary or reasonable to demand that this expertise is available within the operating organisation. As an alternative, it may be acceptable and recommendable for the operating organisation to use consultants and advisory organisations, particularly if the operating organisation is small and the complexity of the radiological protection issues is limited.

(312) Such an arrangement will not in any way relieve the operating organisation of its responsibility. The role of a consultant or an advisory organisation will be to provide information and advice as necessary. It still remains the responsibility of the operating management to take decisions and actions on the basis of such advice, and individual employees still need to adhere to a 'safety culture', constantly asking themselves whether they have done all that they reasonably can to achieve a safe operation.

(313) Similarly, the use of consultants or advisory bodies will not in any way diminish or change the responsibility of the regulatory authority. Furthermore, it will be particularly important when the regulatory authority uses consultants that these are free from any conflicts of interest and are able to provide impartial advice. The need for transparency in decision making should also be kept in mind.

6.6.3. Incident reporting

(314) An accident and incident reporting routine with feedback to users is indispensable in the prevention of emergencies. In order for such a system to work and achieve its goals, mutual trust is required. Licensing constitutes the formal confirmation of a regulatory authority's trust in a user. However, operating organisations also need to be able to trust the regulatory authority. A primary requirement is that all users are treated in a fair and equal manner. Honest reporting of a problem combined with immediate action to rectify the situation should be encouraged, not punished.

6.6.4. Management requirements

(315) The first, and in many ways the most important, of the practical steps in implementing the Commission's Recommendations is the establishment of a safety-based attitude in everyone concerned with all the operations from design to decommissioning. This can only be achieved by a substantial commitment to training and a recognition that safety is a personal responsibility and is of major concern to the top management.

(316) The explicit commitment of an organisation to safety should be made manifest by written policy statements from the highest level of management, by the establishment of formal management structures for dealing with radiological protection,

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by issuing clear operating instructions, and by clear and demonstrable support for those persons with direct responsibility for radiological protection in the workplace and the environment (*Publication 75,* ICRP, 1997a). To translate this commitment into effective action, senior management should identify appropriate design and operational criteria, determine organisational arrangements, assign clear responsibilities to put these policies into effect, and establish a culture within which all those in the organisation recognise the importance of restricting both normal and potential exposures to ionising radiation.

(317) There should be plans for dealing with accidents and emergencies. These plans should be subject to periodic review and exercise, and result in written management requirements. Planning for the event of emergencies should be an integral part of normal operating procedures. Any changes in responsibility, e.g., from the usual line of command to an emergency controller, should be planned in advance. Requirements to, and mechanisms for, implementing lessons learned should be established.

(318) The organisational approach should include involvement and participation of all workers. It is sustained by effective communications and the promotion of competence that enables all employees to make a responsible and informed contribution to the health and safety effort. The visible and active leadership of senior managers is necessary to develop and maintain a culture supportive of health and safety management. The aim is not simply to avoid accidents, but to motivate and empower people to work safely. It is important that management ensures that mechanisms are in place by which workers may provide feedback on radiological protection issues, and workers should be fully involved in developing methods to ensure that doses are as low as reasonably achievable.

(319) Another common responsibility of the operating management is to provide access to occupational services dealing with protection and health. The protection service should provide specialist advice and arrange any necessary monitoring provisions commensurate with the complexity of the operation and its potential hazards. The head of the protection service should have direct access to the senior operating management. The principal role of the occupational health service is the same as it is in any occupation.

6.6.5. Compliance with the intended standard of protection

(320) The measurement or assessment of radiation doses is fundamental to the practice of radiological protection. Neither the equivalent dose in an organ nor the effective dose can be measured directly. Values of these quantities must be inferred with the aid of models, usually involving environmental, metabolic, and dosimetric components. Ideally, these models and the values chosen for their parameters should be realistic, so that the results they give can be described as 'best estimates'. Where practicable, estimates and discussion should be made of the uncertainties inherent in these results (see Section 4.4).

(321) All the organisations concerned with radiological protection should have a duty to verify their compliance with their own objectives and procedures. The

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operating management should establish a system for reviewing its organisational structure and its procedures, a function analogous to financial auditing. National authorities should conduct similar internal audits and should have the added duty of, and authority for, assessing both the level of protection achieved by operating managements and the degree of compliance with the regulatory provisions. All these verification procedures should include consideration of potential exposures by a verification of the safety provisions. Verification procedures should include a review of quality assurance programmes and some form of inspection. However, inspection is a form of sampling – it cannot cover all eventualities. It is best seen as a mechanism for persuading those inspected to put, and keep, their own houses in order.

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7. MEDICAL EXPOSURE OF PATIENTS, COMFORTERS AND CARERS, AND VOLUNTEERS IN BIOMEDICAL RESEARCH

(322) Medical exposures are predominantly delivered to individuals (patients) undergoing diagnostic examinations, interventional procedures, or radiation therapy. Other individuals caring for and comforting patients are also exposed to radiation. These individuals include parents and others, normally family or close friends, who hold children during diagnostic procedures or may come close to patients following the administration of radiopharmaceuticals or during brachytherapy. Exposure to members of the general public from released patients also occurs, but this exposure is almost always very small. In addition, volunteers in biomedical research often undergo medical procedures involving radiation exposure that are similar to procedures performed on patients. Medical exposure refers to all these types of exposures, and the present chapter, in particular, covers the following:

- The exposure of individuals for diagnostic, interventional, and therapeutic purposes, including exposure of the embryo/fetus or infant during medical exposure of patients who are pregnant or breast-feeding;
- Exposures (other than occupational) incurred knowingly and willingly by individuals such as family and close friends helping either in hospital or at home in the support and comfort of patients undergoing diagnosis or treatment;
- Exposures incurred by volunteers as part of a programme of biomedical research that provides no direct benefit to the volunteers.

(323) Radiation exposures of patients in medicine require an approach that differs from the radiological protection in other planned exposure situations. The exposure is intentional and for the direct benefit of the patient. In radiation therapy, the biological effects of high-dose radiation (e.g., cell killing) are used for the benefit of the patient to treat cancer and other diseases. The application of the Commission's Recommendations to the medical uses of radiation therefore requires separate guidance, and medical exposure of patients is therefore dealt with in the present chapter.

(324) In diagnostic and interventional procedures, this means avoiding unnecessary exposures, while in radiation therapy it requires delivery of the required dose to the volume to be treated, avoiding unnecessary exposure of healthy tissues.

(325) The objectives are the justification of medical procedures and the optimisation of protection commensurate with the medical purposes. The Commission's Recommendations for radiological protection and safety in medicine are given in *Publication 73* (ICRP, 1996a), and remain valid. These Recommendations note important differences between the implementation of the system of protection in medicine and its implementation in the other two categories of exposure (occupational and public). These differences include the following.

- The principle of justification applies at three levels in medicine as described in Section 7.1.1.

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- In applying the principle of optimisation of protection of the patient, the benefits and detriments are received by the same individual, the patient, and the dose to the patient is determined principally by the medical needs. Dose constraints for patients are therefore inappropriate, in contrast to their importance in occupational and public exposure. Nevertheless, some management of patient exposure is needed and the use of diagnostic reference levels is recommended in *Publication 73* (ICRP, 1996a) with further guidance in *Supporting Guidance 2* (ICRP, 2001b).
- The limitation of the dose to the individual patient is not recommended because it may, by reducing the effectiveness of the patient's diagnosis or treatment, do more harm than good. The emphasis is then on the justification of the medical procedures and on the optimisation of protection.

(326) The basic framework for protection established in *Publication 60* (ICRP, 1991b) has been further elaborated in a series of publications described below. The recommendations, guidance, and advice in these publications remain valid, forming part of an increasing library of medical exposure information provided by the Commission [see also *Publication 105* (ICRP, 2007b)].

(327) The exposure of patients is deliberate. Except in radiation therapy, it is not the aim to deliver a radiation dose, but rather to use the radiation to provide diagnostic information or to conduct an interventional procedure. Nevertheless, the dose is given deliberately and cannot be reduced indefinitely without prejudicing the intended outcome. Medical uses of radiation are also voluntary in nature, combined with the expectation of direct individual health benefit to the patient. The patient, or legal guardian, agrees or consents to a medical procedure using radiation. This decision is made with varying degrees of informed consent that includes not only the expected benefit but also the potential risks (including radiation). The amount of information provided in order to obtain informed consent varies based on the exposure level (e.g., whether diagnostic, interventional, or therapeutic) and on the possible emergent medical complications that may be attributable to radiation exposure.

(328) The physicians and other health professionals involved in the procedures that irradiate patients should always be trained in the principles of radiological protection, including the basic principles of physics and biology. The final responsibility for the medical exposure of patients lies with the physician, who therefore should be aware of the risks and benefits of the procedures involved.

(329) Medical exposures of patients to external radiation are commonly concerned with limited parts of the body only, and it is important that medical staff are fully aware of the doses to normal tissue in the irradiated fields. Care has to be taken in such situations so that no undesirable tissue reactions occur.

7.1. Justification for medical procedures

(330) Medical exposure of patients calls for a different and more detailed approach to the process of justification. The medical use of radiation should be justified, as is any other planned exposure situation, although that justification lies usually with the medical profession rather than with government or regulatory authorities. The prin-

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cipal aim of medical exposures is to do more good than harm to the patient, subsidiary account being taken of the radiation detriment from the exposure of the radiological staff and of other individuals. The responsibility for the justification of the use of a particular procedure falls on the relevant medical practitioners. Justification of medical procedures therefore remains a principal part of the Commission's Recommendations.

(331) The principle of justification applies at three levels in the use of radiation in medicine.

- At the first level, the use of radiation in medicine is accepted as doing more good than harm to the patient. This level of justification can now be taken for granted and is not discussed further below.
- At the second level, a specified procedure with a specified objective is defined and justified (e.g., chest radiographs for patients showing relevant symptoms, or a group of individuals at risk to a condition that can be detected and treated). The aim of the second level of justification is to judge whether the radiological procedure will usually improve the diagnosis or treatment or will provide necessary information about the exposed individuals.
- At the third level, the application of the procedure to an individual patient should be justified (i.e., the particular application should be judged to do more good than harm to the individual patient). Hence all individual medical exposures should be justified in advance, taking into account the specific objectives of the exposure and the characteristics of the individual involved.

The second and third levels of justification are discussed below.

7.1.1. The justification of a defined radiological procedure (level 2)

(332) The justification of the radiological procedure is a matter for national and international professional bodies, in conjunction with national health and radiological protection authorities and the corresponding international organisations. The possibility of accidental or unintended exposures should also be considered. The decisions should be reviewed from time to time, as more information becomes available about the risks and effectiveness of the existing procedure and about new procedures.

7.1.2. The justification of a procedure for an individual patient (level 3)

(333) Justification of individual exposures should include checking that the required information is not already available and that the proposed examination is the most suitable method of providing the clinical information required. For high-dose examinations, such as complex diagnostic and interventional procedures, individual justification is particularly important and should take account of all available information. This includes the details of the proposed procedure and of alternative procedures, the characteristics of the individual patient, the expected dose to the patient, and the availability of information on previous or expected examinations or

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treatment. It will often be possible to speed up the justification process by defining referral criteria and patient categories in advance.

7.2. Optimisation of protection in medical exposures

(334) The Commission now uses the same conceptual approach in source-related protection, irrespective of the type of source. In the case of exposure from diagnostic and interventional medical procedures, the *diagnostic reference level* has as its objective the optimisation of protection, but it is not implemented by constraints on individual patient doses. It is a mechanism to manage patient dose to be commensurate with the medical purpose (see Section 7.2.1).

7.2.1. Diagnostic reference levels

(335) Diagnostic reference levels apply to radiation exposure of patients resulting from procedures performed for medical imaging purposes. They do not apply to radiation therapy. Diagnostic reference levels have no direct linkage to the numerical values of the Commission's dose limits or dose constraints. In practice, the values are selected on the basis of a percentile point on the observed distribution of doses to patients or to a reference patient. The values should be selected by professional medical bodies in conjunction with national health and radiological protection authorities and reviewed at intervals that represent a compromise between the necessary stability and the long-term changes in the observed dose distributions. The selected values could be specific to a country or region.

(336) Diagnostic reference levels are used in medical imaging to indicate whether, in routine conditions, the levels of patient dose from, or administered activity (amount of radioactive material) for, a specified imaging procedure are unusually high or low for that procedure. If so, a local review should be initiated to determine whether protection has been adequately optimised or whether corrective action is required (ICRP, 1996a). The diagnostic reference level should be expressed as a readily measurable patient-dose-related quantity for the specified procedure. Screening programmes, such as mammography of asymptomatic women in the general population, may require different diagnostic reference levels from the clinical use of similar diagnostic methods. Additional guidance is given in *Publication 105* (ICRP, 2007b) and in *Supporting Guidance 2* (ICRP, 2001b).

(337) In principle, it might be possible to choose a lower diagnostic reference level below which the doses would be too low to provide a sufficiently good image quality. However, such diagnostic reference levels are difficult to set, because factors other than dose also influence image quality. Nevertheless, if the observed doses or administered activities are consistently far below the diagnostic reference level, there should be a local review of the quality of the images obtained.

(338) Extensive information on the management of patient dose in fluoroscopically guided interventional procedures, computed tomography and digital radiology is provided in *Publications 85*, *87*, and *93*, respectively (ICRP, 2000b, 2000d, 2004a).

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7.2.2. Radiation therapy

(339) In radiation therapy, optimisation involves not only delivering the prescribed dose to the tumour, but also planning the protection of healthy tissues outside the target volume. These radiation therapy issues are considered in *Publication 44* (ICRP, 1985a).

7.3. Effective dose in medical exposure

(340) The age distributions for workers and the general population (for which the effective dose is derived) can be quite different from the overall age distribution for the patients undergoing medical procedures using ionising radiation. The age distribution also differs from one type of medical procedure to another, depending on the prevalence of the individuals for the medical condition being evaluated. For these reasons, risk assessment for medical diagnosis and treatment using ionising radiation is best evaluated using appropriate risk values for the individual tissues at risk and for the age and sex distribution of the individuals undergoing the medical procedures. Effective dose can be of value for comparing the relative doses from different diagnostic procedures and for comparing the use of similar technologies and procedures in different hospitals and countries as well as the use of different technologies for the same medical examination, provided that the reference patient or patient populations are similar with regard to age and sex.

(341) The assessment and interpretation of effective dose from medical exposure of patients is problematic when organs and tissues receive only partial exposure or a very heterogeneous exposure, which is the case especially with diagnostic and interventional procedures.

7.4. Exposure of patients who are pregnant

(342) Before any procedure using ionising radiation, it is important to determine whether a female patient is pregnant. The feasibility and performance of medical exposures during pregnancy require specific consideration owing to the radiation sensitivity of the developing embryo/fetus.

(343) Prenatal doses from most correctly performed diagnostic procedures present no measurably increased risk of prenatal or postnatal death, developmental damage including malformation, or impairment of mental development over the background incidence of these entities. Life-time cancer risk following in-utero exposure is assumed to be similar to that following irradiation in early childhood. Higher doses such as those involved in therapeutic procedures have the potential to result in developmental harm (see Section 3.4).

(344) The pregnant patient has a right to know the magnitude and type of potential radiation effects that might result from in-utero exposure. Almost always, if a diagnostic radiology examination is medically indicated, the risk to the mother of not doing the procedure is greater than the risk of potential harm to the embryo/fetus. However, some procedures and some radiopharmaceuticals that are used in

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nuclear medicine (e.g., radioiodides) can pose increased risks to the embryo/fetus. The Commission has given detailed guidance in *Publication 84* (ICRP, 2000a).

(345) It is essential to ascertain whether a female patient is pregnant prior to radiation therapy and some abdominal interventional procedures. In pregnant patients, cancers that are remote from the pelvis can usually be treated with radiation therapy. This however requires particular attention in treatment planning. The expected radiation dose to the embryo/fetus, including the scattering component, must be estimated. Cancers in the pelvis can rarely be adequately treated with radiation therapy during pregnancy without severe or lethal consequences for the embryo/fetus.

(346) Termination of pregnancy owing to radiation exposure is an individual decision affected by many factors. Absorbed doses below 100 mGy to the embryo/fetus should not be considered a reason for terminating a pregnancy. At embryonic/fetal doses above this level, the pregnant patient should receive sufficient information to be able to make informed decisions based upon individual circumstances, including the magnitude of the estimated embryonic/fetal dose and the consequent risks of serious harm to the developing embryo/fetus and risks of cancer in later life.

(347) Radiation risks after prenatal radiation exposure are discussed in detail in *Publication 90* (ICRP, 2003a). The exposure of patients who are pregnant is dealt with in detail in *Publication 84* (ICRP, 2000a) and in *Publication 105* (ICRP, 2007b), which also discuss the considerations to be taken into account regarding termination of pregnancy after radiation exposure. Radiation exposure of pregnant females in biomedical research is discussed in Section 7.7.

7.5. Accident prevention in external beam therapy and brachytherapy

(348) Accident prevention in external beam therapy and brachytherapy should be an integral part of the design of equipment and premises and of the working procedures. A key focus of accident prevention has long been the use of multiple defences against the consequences of failures. This approach, called 'defence in depth', is aimed at preventing equipment failures and human errors and mitigating their consequences, should they happen. The Commission has given extensive advice on reducing the probability of potential exposure and preventing accidents in *Publications 76, 86, 97* and *98* (ICRP, 1997b, 2000c, 2005b, 2005c).

7.6. Protection of carers and comforters of patients treated with radionuclides

(349) Unsealed radionuclides are used in the diagnosis and treatment of various diseases in the form of radiopharmaceuticals that are given to the patient by injection, ingestion, or inhalation. These radiopharmaceuticals may localise in body tissues until they decay or they may be eliminated through various pathways (e.g., urine). Sealed sources are implanted in the patient's body.

(350) Precautions for the public are rarely required after diagnostic nuclear medicine procedures but some therapeutic nuclear medicine procedures, particularly those involving iodine–131, can result in significant exposure to other people, espe-

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cially those involved in the care and support of patients. Hence, members of the public caring for such patients in hospital or at home require individual consideration.

(351) *Publication 94* (ICRP, 2004b) provides recommendations for the release of patients after therapy with unsealed radionuclides. These recommendations include that young children and infants, as well as visitors not engaged in direct care or comforting, should be treated as members of the public for radiological protection purposes (i.e., be subject to the public dose limit of 1 mSv/year). For individuals directly involved in comforting and caring, other than young children and infants, a dose constraint of 5 mSv per episode (i.e., for the duration of a given release after therapy) is reasonable. The constraint needs to be used flexibly. For example, higher doses may well be appropriate for parents of very sick children.

(352) The thyroid gland of persons under the age of 15 is more radiosensitive than that of adults, so that particular care should be taken to avoid the contamination of infants, children, and pregnant women from patients treated with radioiodine.

(353) The decision to hospitalise or release a patient after therapy should be made on an individual basis considering several factors including residual activity in the patient, patient's wishes, family consideration (particularly the presence of children), environmental factors, and existing guidance and regulations. *Publication 94* (ICRP, 2004b) comments on the use of holding tanks for the storage of urine, implying that their use is unnecessary.

(354) The unintentional exposure of members of the public in waiting rooms and on public transport usually is not high enough to require special restrictions on nuclear medicine patients, except for those being treated with radioiodine (*Publications 73* and *94*, ICRP, 1996a, 2004b).

(355) In principle, similar reasoning applies when patients are treated with permanently implanted sealed sources. However, the available data show that, in the vast majority of cases, the dose to comforters and carers remains well below a value of 1 mSv/year except for the rare case where the patient's partner is pregnant at the time of implantation and the anticipated dose to the pregnant partner could exceed 1 mSv in a year (*Publication 98*, ICRP, 2005c).

(356) If the patient dies in the first few months after implantation of a sealed source, cremation of the corpse (frequent in some countries) raises several issues related to: 1) the radioactive material that remains in the patient's ashes; and 2) the radioactive material that is released into the air, potentially inhaled by crematorium staff or members of the public. Available data shows that cremation can be allowed if 12 months have elapsed since implantation with iodine–125 (3 months for palladium–103). If the patient dies before this delay has elapsed, specific measures should be undertaken (ICRP, 2005c).

7.7. Volunteers for biomedical research

(357) Volunteers make a substantial contribution to biomedical research. Some of the research studies are of direct value in the investigation of disease; others provide information on the metabolism of pharmaceuticals and of radionuclides that may be absorbed from contamination of the workplace or the environment. Not all these

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studies take place in medical institutions, but the Commission includes the exposure of all volunteers in biomedical research under the category of medical exposure.

(358) The ethical and procedural aspects of the participation of volunteers in biomedical research and its justification have been addressed by the Commission in *Publication 62* (ICRP, 1991c). That report also discusses dose constraints for volunteers under different conditions, as briefly summarised in Table 8 (Chapter 6).

(359) In many countries, radiation exposure of pregnant females as subjects in biomedical research is not specifically prohibited. However, their involvement in such research is very rare and should be discouraged unless pregnancy is an integral part of the research. For the protection of the embryo/fetus, strict controls should be placed on the use of radiation in these cases.

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8. PROTECTION OF THE ENVIRONMENT

(360) Interest in the protection of the environment has greatly increased in recent years, in relation to all aspects of human activity. Such interest has been accompanied by the development and application of various means of assessing and managing the many forms of human impact upon it. The Commission is thus aware of the growing need for advice and guidance on such matters in relation to radiological protection even though such needs have not arisen from any new or specific concerns about the effects of radiation on the environment. The Commission also recognises that there is a current lack of consistency at international level with respect to addressing such issues in relation to radioactivity, and therefore believes that a more proactive approach is now necessary.

8.1. The objectives of radiological protection of the environment

(361) The Commission acknowledges that, in contrast to human radiological protection, the objectives of environmental protection are both complex and difficult to articulate. The Commission does however subscribe to the global needs and efforts required to maintain biological diversity, to ensure the conservation of species, and to protect the health and status of natural habitats, communities, and ecosystems. It also recognises that these objectives may be met in different ways, that ionising radiation may be only a minor consideration – depending on the environmental exposure situation – and that a sense of proportion is necessary in trying to achieve them.

(362) The Commission has previously concerned itself with mankind's environment only with regard to the transfer of radionuclides through it, primarily in relation to planned exposure situations, because this directly affects the radiological protection of human beings. In such situations, it has been considered that the standards of environmental control needed to protect the general public would ensure that other species are not put at risk, and the Commission continues to believe that this is likely to be the case.

(363) However, the Commission considers that it is now necessary to provide advice with regard to all exposure situations. It also believes that it is necessary to consider a wider range of environmental situations, irrespective of any human connection with them. The Commission is also aware of the needs of some national authorities to demonstrate, directly and explicitly, that the environment is being protected, even under planned situations.

(364) The Commission therefore believes that the development of a clearer framework is required in order to assess the relationships between exposure and dose, and between dose and effect, and the consequences of such effects, for non-human species, on a common scientific basis. This issue was first discussed in *Publication 91* (ICRP, 2003b), and it was concluded that it was necessary to draw upon the lessons learned from the development of the systematic framework for the protection of human beings. This framework is based on an enormous range of knowledge that the Commission attempts to convert into pragmatic advice that will be of value in

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managing different exposure situations, bearing in mind the wide range of errors, uncertainties, and knowledge gaps of the various databases.

(365) The advantage of such a comprehensive and systematic approach is that, as the needs for change to any component of the system arise (as in the acquisition of new scientific data, or changes in societal attitudes, or simply from experience gained in its practical application) it is then possible to consider what the consequences of such a change may be elsewhere within the system, and upon the system as a whole. Such an approach would not work unless it was based on a numerical framework that contained some key points of reference.

8.2. Reference Animals and Plants

(366) In the case of human radiological protection, the Commission's approach to such issues has been greatly assisted by the development of anatomical and physiological reference models (ICRP, 2002). It has concluded that a similar approach would be of value as a basis for developing further advice and guidance for the protection of other species. The Commission is therefore developing a small set of Reference Animals and Plants (Pentreath, 2005), plus their relevant databases, for a few types of organisms that are typical of the major environments. Such entities will form the basis of a more structured approach to understanding the relationships between exposures and dose, dose and effects, and the potential consequences of such effects.

(367) The Reference Animals and Plants can be considered as hypothetical entities with certain assumed basic biological characteristics of a particular type of animal or plant, as described to the generality of the taxonomic level of Family, with defined anatomical, physiological, and life-history properties. They are not, therefore, necessarily the *direct* objects of protection themselves but, by serving as points of reference, they should provide a basis upon which some management decisions could be made. Simple dosimetric models, plus relevant data sets, are currently being developed for different stages of the life cycle of each type. Available data on radiation effects for each type are also being reviewed.

(368) Some form of practical means is obviously required in order to make judgements, based on our current level of knowledge of the effects of radiation on different types of animals and plants, in order to meet the Commission's objectives. With the exception of mammals, however, there is a general paucity of information upon which dose-response relationships can be established that would enable sensible conclusions to be drawn, particularly with respect to the relatively low dose rates likely to obtain in most exposure situations. Indeed, in general, the databases on radiation effects for the majority of animals and plants are not dissimilar to those relating to 'chemical toxicity' studies, where the levels required to produce a given effect are many orders of magnitude greater than those expected in the majority of environmental situations.

(369) With radiation there is another source of reference, and that is the natural background radiation to which such animals and plants are continuously and 'typically' exposed. Thus additional radiation doses to animals and plants can be

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compared with those dose rates known or expected to have certain biological effects in those types of animals and plants, and with the dose rates normally experienced by them in their natural environments.

(370) The Commission does not therefore propose to set any form of 'dose limits' with respect to environmental protection. By setting out data for some Reference Animals and Plants, in a transparently derived way, and upon which further action may be considered, the Commission intends to offer more practical advice than in the past. The Commission will use this framework to gather and interpret data in order to provide more comprehensive advice in the future, particularly with regard to those aspects or features of different environments that are likely to be of concern under different radiation exposure situations.

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ANNEX A. BIOLOGICAL AND EPIDEMIOLOGICAL INFORMATION ON HEALTH RISKS ATTRIBUTABLE TO IONISING RADIATION: A SUMMARY OF JUDGEMENTS FOR THE PURPOSES OF RADIOLOGICAL PROTECTION OF HUMANS

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Preface to Annex A

When the Commission initiated its project to review and update its 1990 Recommendations, at the Main Commission meeting in Cape Town, South Africa, in 1998, it was clear from the outset that the main text of the new Recommendations would need to be supported by scientific Annexes and reports in much the same manner as the 1990 Recommendations.

Therefore, ICRP Committees 1 (on radiation effects) and 2 (on doses from radiation exposure) were asked to outline and begin to draft Annexes on the health effects of radiation and on dosimetric considerations. (Committees 3 on protection in medicine and 4 on the application of ICRP recommendations were similarly asked to produce supporting documents which were and are being published as separate reports: *Publication 105*, ICRP 2007b on protection in medicine and *Publication 101*, ICRP 2006a, on assessing dose to the representative person and on optimisation).

After initial plenary work, Committee 1 formed a Task Group in 2001 to advise the Main Commission and draft the present Annex to the Recommendations.

The membership of the Task Group was as follows:

R. Cox, Chairman	J. Hendry	A. Kellerer
C. Land	C. Muirhead	D. Preston
J. Preston	E. Ron	K. Sankaranarayanan
R. Shore	R. Ullrich	

The corresponding members were:

A. Akleyev	M. Blettner	R. Clarke
J.D. Harrison	R. Haylock	J. Little
H. Menzel	O. Niwa	A. Phipps
J. Stather	F. Stewart	C. Streffer
M. Tirmarche	P. Zhou	

The membership of ICRP Committee 1 during the preparation of this Annex was:

(2001-2005)

R. Cox, Chairman	A. Akleyev	M. Blettner
J. Hendry	A. Kellerer	C. Land
J. Little	C. Muirhead, Secretary	O. Niwa
D. Preston	J. Preston	E. Ron
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(2005-2009)

J. Preston, Chairman	A. Akleyev	M. Blettner
R. Chakraborty	J. Hendry, Secretary	W. Morgan
C. Muirhead	O. Niwa	D. Preston
E. Ron	W. Rühm	R. Shore
F. Stewart	M. Tirmarche	R. Ullrich, Vice-Chairman
P.-K. Zhou		

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Principal conclusions and recommendations

The following summary statements relate largely to health effects attributable to radiation in the dose range up to around 100 mSv (as single or annual doses) for the purposes of radiological protection.

- **For the induction of cancer and heritable disease at low doses/low dose rates the use of a simple proportionate relationship between increments of dose and increased risk is a scientifically plausible assumption; uncertainties on this judgement are recognised.**
- **A dose and dose-rate effectiveness factor (DDREF) of 2 recommended in *Publication 60* (ICRP, 1991b) should be retained for radiological protection purposes; the effect of introducing the possibility of a low-dose threshold for cancer risk is judged to be equivalent to that of an uncertain increase in the value of DDREF.**
- **Proposed changes in radiation weighting factors for protons and neutrons are noted; these judgements are discussed in Annex B to the present Recommendations: 'Quantities used in radiological protection'.**
- **New radiation detriment values and tissue weighting factors (w_T) have been proposed; the most significant changes from *Publication 60* relate to breast, gonads, and the treatment of remainder tissues. The w_T changes in question are: breast (0.12 from 0.05); gonads (0.08 from 0.20); remainder tissues (0.12 from 0.05 using a new additive system).**
- **Based upon cancer incidence data, detriment adjusted nominal risk coefficients for cancer are 5.5 10^{-2} Sv^{-1} for the whole population and 4.1 10^{-2} Sv^{-1} for adult workers; the respective *Publication 60* values are 6.0 10^{-2} Sv^{-1} and 4.8 10^{-2} Sv^{-1}.**
- **Detriment adjusted probability coefficients for heritable disease up to the second generation are 0.2 10^{-2} Sv^{-1} for the whole population and 0.1 10^{-2} Sv^{-1} for adult workers; the respective *Publication 60* values are 1.3 10^{-2} Sv^{-1} and 0.8 10^{-2} Sv^{-1} but these relate to risks at a theoretical equilibrium and no longer seem justified.**
- **Cancer risk following in-utero exposure is judged to be no greater than that following exposure in early childhood.**
- **Knowledge of the roles of induced genomic instability, bystander cell signalling and adaptive response in the genesis of radiation–induced health effects is insufficiently well developed for radiological protection purposes; in many circumstances these cellular processes will be incorporated in epidemiological measures of risk.**
- **Genetic susceptibility to radiation-induced cancer involving strongly expressed genes is judged to be too rare to appreciably distort estimates of population risk; the potential impact of common but weakly expressing genes remains uncertain.**
- **Dose responses for radiation-induced tissue reactions (deterministic effects) in adults and children are, in general, judged to have true dose thresholds which result in the absence of risk at low doses; further consideration of the extent of the dose threshold for cataract induction (visual impairment) is recommended.**
- **Dose responses for in-utero radiation-induced tissue reactions, malformations and neurological effects are also judged to show dose thresholds above around 100**

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mGy; uncertainty remains on the induction of IQ deficits but at low doses the risk is judged to be of no practical significance.

- **Risks of non-cancer disease at low doses remain most uncertain and no specific judgement is possible.**

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A.1. Introduction

(A 1) Since the publication of the 1990 Recommendations of the ICRP (*Publication 60*, ICRP 1991b), ICRP Committee 1 has continued to maintain broad surveillance on scientific developments regarding the quantification of health effects attributable to radiation exposure and the biological mechanisms that underlie these effects. Much of the output of Committee 1 is represented in the reports of ICRP Task Groups, and Committee 1 Working Parties have reviewed data in other relevant areas.

(A 2) The purpose of the present Annex is to summarise all post–1990 Committee 1 judgements relating to the health effects of radiation in order to support the development by the Commission of its new Recommendations. In many of the areas considered in the present Annex, Committee 1 had already provided specific judgements, e.g., on the risk of multifactorial diseases (*Publication 83*, ICRP 1999b), on radiation weighting factors (*Publication 92*, ICRP 2003c) and on cancer risk at low doses (*Publication 99*, ICRP 2005d). However, the revision of a) judgements on the induction of tissue reactions; b) nominal risk coefficients for risks of cancer and heritable disease; c) the transport of cancer risk between different populations; and d) the choice of tissue weighting factors required much additional work. For this reason the above topics are covered in detail in this Annex.

(A 3) An additional feature of the present Annex is the extent to which the accumulation of epidemiological and biological knowledge since 1990 has served to strengthen some of the judgements made in *Publication 60* or, in some cases, has led to a revision in procedures for risk estimation. In spite of the detailed nature of these gains in knowledge, the principal objective of this Annex is the provision of broad judgements for practical purposes of radiological protection. Accordingly, much of the work presented here centres on the continuing use of effective dose as a radiological protection quantity for prospectively estimating risks in the population and to demonstrate compliance with dose limits. The application of the concept of effective dose is discussed in Annex B.

(A 4) The Annex is structured in the following way. Section A.2 provides a brief summary of the gains in knowledge since 1990 on the biological processes that underlie the health effects of radiation exposure. Section A.3 provides updated judgements on the mechanisms and risks of radiation-induced tissue reactions. Section A.4 considers the mechanisms and genetics of cancer induction, summarises previous judgements on radiation weighting factors and details new epidemiologically based judgements on nominal risk coefficients, transport of risk, radiation detriment and tissue weighting factors; Section A.4 also summarises an earlier judgement on cancer risk in utero. Section A.5 briefly considers non-cancer diseases after radiation. In Section A.6, the Annex details a newly developed approach to the estimation of risks of heritable disease and provides a revised estimate of this risk. Finally, in Section A.7, a simple tabular format is used to summarise the principal recommendations of the Annex and to map these judgements to the appropriate sections of the Annex.

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A.1.1. References, Preface and Section A.1

ICRP, 1991b. The 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21 (1–3).

ICRP, 1999b. Risk estimation for multifactorial diseases. ICRP Publication 83. Ann. ICRP 29 (3–4).

ICRP, 2003c. Relative biological effectiveness (RBE), quality factor (Q) and radiation weighting factor (w_R). ICRP Publication 92. Ann. ICRP 33 (4).

ICRP, 2005d. Low-dose extrapolation of radiation-related cancer risk. ICRP Publication 99. Ann. ICRP 35 (4).

ICRP, 2006a. Assessing dose of the representative person for the purpose of radiation protection of the public *and* The optimisation of radiological protection: Broadening the process. ICRP Publication 101. Ann. ICRP 36 (3).

ICRP, 2007b. Radiological protection in medicine. ICRP Publication 105. Ann. ICRP 37 (5).

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A.2. Interactions of radiation with cells and tissues

(A 5) The purpose of this Section is to summarise knowledge on the interactions of radiation with cells and tissues in the body with emphasis on the information and concepts that have developed since 1990. The intention is to provide a biological framework for the judgements to be developed in subsequent sections of the Annex. Although some of these biological data and concepts are complex, much of this Annex is intended for the non-specialist reader. Consequently the Annex will not enter into the detail of many of the biological and biophysical debates but rather seeks clarity and simplicity on the judgements made. Details of these debates may be found in earlier ICRP publications and other reviews.

A.2.1. Biophysical aspects of radiation action on cells

(A 6) ICRP has not specifically reviewed the broad topics of radiation biophysics and microdosimetry since 1990 but important advances and judgements are given in *Publication 92* (ICRP, 2003c) and in an ICRP Task Group report on Low-dose risks (*Publication 99*, ICRP, 2005d). The understanding of the early post-irradiation biophysical processes in cells and tissues has advanced substantially and the following paragraphs briefly highlight some major points of development. Further information is available in *Publication 92* (ICRP, 2003c), *Publication 99* (ICRP, 2005d), Goodhead et al. (1996) and NAS/NRC (2006).

(A 7) Knowledge of the fine structure of energy deposition from radiation tracks in DNA dimensions has grown, largely through the further development of Monte-Carlo track structure codes. Coupled with radiobiological information, track structure data have impacted greatly on thinking in respect of the nature of biologically critical damage to DNA.

(A 8) In particular, it has been recognised that a high proportion of radiation-induced damage in DNA is represented in complex clusters of chemical alterations. Such clustered damage can arise via a combination of damages induced by the main tracks, secondary electrons and secondary reactive radical species. Double- and single-strand breaks (DSB and SSB) in the DNA sugar-phosphate backbone plus a variety of damaged DNA bases can combine together in clusters, with a substantial fraction of total damage being closely spaced. There is also evidence that both the frequency and the complexity of complex clustered damage depends upon the linear energy transfer (LET) of the radiation.

(A 9) When DSB, SSB and base damages are considered together, complex clustered damage may constitute as much as 60% and 90% of total DNA damage after low and high LET radiations respectively. These data highlight a major difference between DNA lesions induced by radiation and those arising spontaneously via oxidative attack by reactive chemical radicals. Whereas the former are predominantly complex and clustered, the latter are randomly distributed and simple in their chemical structure.

(A 10) As described in ICRP *Publication 99* and noted in Section A.4.1, the different repair characteristics of simple and complex DNA lesions are an important

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factor in the development of judgements on health effects after low doses of radiation.

(A 11) In addition to improvements in our understanding of the induction of complex DNA damage by radiation there have been other advances in radiation biophysics. For example, radiation-induced damage has been investigated at the level of chromosome structure, and this work has been paralleled by the biophysical modelling of the induction of gene/chromosomal mutations. There has also been valuable technical innovation including the development of single particle irradiation systems (microbeams) and of imaging methods for the cellular visualisation of DNA-protein interactions during DNA damage response (see *Publication 99,* ICRP, 2005d; Cherubini et al., 2002).

A.2.2. Chromosomal DNA as the principal target for radiation

(A 12) In addition to the biophysical information outlined in Section A.2.1, there is more direct evidence that implicates chromosomal DNA as the principal cellular target for biological effects. Much of the early evidence on this issue concerned the greater radiobiological effectiveness of radionuclides incorporated into DNA in the cell nucleus as compared with cellular proteins in general (UNSCEAR 1993). More recently the use of microbeam irradiation facilities capable of delivering a defined dose to different parts of the cell has fully confirmed the radiosensitivity of the cell nucleus. However, as noted in Section A.2.5, these microbeam techniques have also provided evidence of the potential complexity of cellular radiation response.

(A 13) In addition, since 1990 the critical importance of DNA damage for radiobiological effects, including cancer induction, has been emphasised by a large number of studies with cells and animals that are genetically deficient in DNA damage response – many of these specific genetic deficiencies increase the frequency of radiobiological effects (UNSCEAR 1993, 2000; *Publication 79*, ICRP 1998a; NAS/NRC 2006). Finally the rapidly developing concordance noted in Section A.2.1 between biophysical predictions on radiation action, the biological importance of complex DNA damage and the characteristics of radiation-induced gene and chromosomal mutations add weight to the conclusion that certain forms of DNA damage are critically important to radiobiological effects.

A.2.3. DNA damage response and repair

DNA repair, apoptosis, and cellular signalling

(A 14) Advances in knowledge of the mechanisms and consequences of post-irradiation processes in cells arguably represent the most profound change in our understanding of radiobiology. Much of this advance can be ascribed to the greatly improved technology and knowledge base that is now characteristic of modern cell/molecular biology and genetics. The UNSCEAR 2000, NCRP 2001, NAS/NRC 2006 and ICRP 2005d (*Publication 99*) reports deal with these issues in detail and only a few key conclusions are given here.

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- The isolation and characterisation of critical DNA damage response genes, e.g., for ATM, NBS and DNA PK_{cs} proteins, have provided insights into the structure and function of the most important biochemical pathways that operate to recognise and signal the presence of DNA damage.
- There is now good understanding of many of these pathways and this leads to the view that error-prone repair of chemically complex DNA double-strand lesions best explains the cellular radiobiological responses known for many years, viz., the induction of chromosome aberrations, gene mutation, and cell killing.
- The potential for error-free, recombinational repair of radiation-induced DNA double-strand lesions is recognised but, since it is thought to be restricted to the later phases of the cell cycle, its impact on radiation risk overall is not likely to be great.
- Coupled with earlier cellular studies, molecular and biochemical data add weight to the view that the activity of DNA damage response and repair processes are major determinants of dose/dose rate and radiation quality effects in cells.
- Post-irradiation programmed cell death (apoptosis) and delaying effects on the passage of cells through their reproductive cycles are now much better understood at the molecular and biochemical levels.
- In terms of protective effects, apoptotic elimination of radiation damaged cells may be viewed as an alternative to repair, i.e., apoptotic death reduces the frequency of viable cells carrying mutations.
- The imposition of cell cycle checkpoints in irradiated cells has been biochemically linked with the complex network of DNA damage signalling and may serve to maximise opportunities for repair or as points where the cell decides its fate (life or death) on the basis of biochemical balance. The evidence for this is, however, limited.
- New highly sensitive techniques for studying the induction of DNA double-strand breaks in single cells and post-irradiated cellular signalling show great promise for gaining knowledge of DNA damage response at low doses.

(A 15) A critical element in the advances that underpin the above judgements is the now compelling evidence that perturbation of DNA damage response/repair and apoptotic/cell cycle control are often closely associated with tumorigenic development. This concept gives increased confidence that these cellular activities are integral to the cellular defences mounted against post-irradiation tumour development. This in turn means that the characteristics of these cellular processes are important elements in the development of judgements in radiological protection.

Adaptive responses

(A 16) The relatively high level of knowledge gained on post-irradiation DNA repair, apoptosis and cellular signalling may be contrasted with the continuing uncertainty on the mechanisms and significance of so-called adaptive responses. Typically, in some experimental systems, adaptive responses are seen in cells conditioned by a priming dose of radiation. In some way this conditioning dose allows cells to develop increased resistance to a second radiation challenge.

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(A 17) Data relating to adaptive responses of various types have been reviewed extensively (UNSCEAR 1994, 2000, NCRP 2001, NAS/NRC 2006, ICRP 2005d). The principal conclusions from these reviews may be summarised as follows:

- Adaptive responses are not a universal feature of cells in vitro or in vivo.
- Even in the most well-studied cellular system (cytogenetic response in human lymphocytes) there is a) no evidence that adaptive responses may be triggered by doses of a few tens of milligray and b) there is considerable donor variation in the expression of the response.
- Although some studies support an association with more general stress response mechanisms, chemical radical scavenging and/or more efficient DNA repair, mechanistic knowledge of adaptive responses remains fragmentary.
- Although there are some positive results, animal studies on tumour induction (and immune response) do not provide consistent evidence of adaptive responses that reduce adverse health effects.

A.2.4. The induction of gene and chromosomal mutations

(A 18) As noted earlier there are now strong links between the biophysical processes that determine the induction of complex DNA double-strand lesions, error-prone DNA damage response/repair processes and the forms of gene and chromosomal mutations (DNA sequence loss or rearrangement) characteristic of ionising radiation exposure. Much of the available quantitative dose-response data for cells pre-date *Publication 60*, and the specific forms of mutational dose response recorded depend upon the biological system, the mutational endpoint, the radiation quality (LET) and the dose rate (Thacker et al., 1992, UNSCEAR, 1993, 2000).

(A 19) In general, however, mutational dose-responses are linear-quadratic for low LET, and tend towards linearity as LET increases. For low LET radiations, reduction in dose rate usually reduces the frequency of induced gene/chromosomal mutations in mammalian somatic and germ cells. The maximum dose-rate reduction factor is usually 3–4 but it can be somewhat higher for chromosome aberration induction in human lymphocytes. A reasonably consistent relationship between RBE and LET for mutation induction has also been recorded with maximum values for RBE of around 10–20 usually being seen in the LET range 70–200 keV μm^{-1}.

(A 20) A novel feature of recent studies involving 'chromosome painting' techniques is that complex chromosome exchanges involving the interaction of more than two breakpoints are infrequent at low doses of low LET radiation but can be a significant fraction of high LET induced events at all doses. Advances in the understanding of radiation action on cellular DNA has included modelling of the formation of chromosomal exchanges but contention remains as to whether these exchanges demand the interaction of two damaged sites or whether a significant fraction derives from the interaction of damaged and undamaged sites (UNSCEAR 2000). Since 1990 considerable effort has been made to investigate the induction of gene and chromosomal mutations at low doses. There are many

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technical factors that limit the resolution of such low-dose effects but two studies are notable.

(A 21) First, a large-scale investigation of chromosome aberration induction by x rays in human lymphocytes provided evidence of a linear dose-response at low doses with a limit of resolution of around 20 mGy. Second, the use of a highly sensitive in-vivo mutation system relating to pigment-producing cells in mouse skin showed linearity of mutational dose response down to the lowest x-ray doses of around 50 mGy (see UNSCEAR 2000, ICRP 2005d).

(A 22) There have also been valuable developments in the use of chromosomal aberration not only as a biomarker of radiation exposure but also for the purposes of establishing relationships between in-vivo cellular response, dose/dose-rate effects and potential health outcomes (Tucker et al., 1997, Tawn et al., 2004).

A.2.5. Epigenetic responses to radiation

(A 23) A major feature of radiobiological research since 1990 has been a range of studies that provide evidence of post-irradiation cellular responses that appear to result in genomic change and/or cellular effect without an obvious requirement for directly induced DNA damage (see Cherubini et al. 2002, NAS/NRC 2006, ICRP 2005d). In a broad sense these processes may be termed epigenetic and they contrast with the well-established radiobiological concept of direct DNA targeting by ionising radiation tracks which has underpinned much of the post-1990 developments in biophysics and DNA damage response. Although there are elements of overlap, these epigenetic effects may be placed in two categories: a) radiation-induced genomic instability; b) post-irradiation bystander signalling between cells.

Radiation-induced genomic instability

(A 24) Whereas conventional DNA damage response is known to result in the expression of genomic damage within the first or second post-irradiation cell cycles, the term 'induced genomic instability' broadly describes a set of phenomena whereby genomic damage and its cellular consequences are expressed persistently over many post-irradiation cell cycles (Little 2003, Morgan 2003). This instability, as expressed in cultured cells, can take the form of increased frequencies of chromosome aberrations, gene mutations and apoptosis/cell death; other manifestations have also been recorded. *Publication 99* (ICRP 2005d) and the NAS/NRC (2006) report have reviewed the recent evidence concerning induced genomic instability including the examples noted below.

(A 25) Much of the in-vitro cellular work on induced genomic instability has been performed using chromosomal endpoints. Although persistent chromosomal instability has been reproducibly demonstrated in mass cultures of established cell lines, there have been fewer studies of clonal cell populations and normal diploid cells. In this context a recent cytogenetic study with human diploid fibroblasts using mass culture and clonal techniques was particularly revealing in that it found no evidence of instability phenomena.

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(A 26) This negative result raises the possibility that induced genomic instability is preferentially expressed in abnormal or genetically altered cells, and this would be consistent with the difficulties experienced in clearly demonstrating the phenomenon in vivo. After in-vivo exposure of humans and mice to high and low LET radiations, cytogenetic results have been negative or showed inconsistent evidence of persistent instability in haemopoietic cells. Nevertheless there are some positive results in certain mouse strains and normal cells, and further work is called for. In addition, there are indications that, in mice, the expression of induced genomic instability varies with genetic background and, in some cases, it may associate with deficiency in DNA damage response.

(A 27) The biological basis for induced genomic instability in its various forms is not well understood. Some biochemical data suggest the involvement of cellular stress and oxidative processes; other cytogenetic studies implicate potentially unstable DNA segments encoding DNA repeat sequences.

Post-irradiation bystander signalling

(A 28) The so-called bystander effect relates to the expression of cell death/apoptosis, gene/chromosomal mutation, genomic instability and/or changing patterns of protein abundance in cells not directly intersected by radiation tracks (see Little, 2003, Morgan, 2003, Mothersill and Seymour, 2001). These bystander cells are believed to be responding to signals from their irradiated neighbours via intercellular communication mediated by molecules passing through gap junctions in adjoining cell membranes or via diffusion of these signalling molecules through the cell culture medium. Data relating to the bystander effects of radiation are reviewed in *Publication 99* (ICRP, 2005d) and the NAS/NRC (2006) report and only a few points are noted here.

(A 29) Experimental studies on the bystander effect in cultured cells have been greatly facilitated by the development of microbeam irradiation facilities which allow the delivery of defined numbers of radiation tracks to cells or their nuclei. In this way, cellular effects arising in unirradiated cells may be specifically determined. Alternatively cells may be irradiated in mass culture with a fluence of particles that allows for only a fraction of cells/cell nuclei to be intersected. The expression of bystander signalling is then evidenced by a frequency of cellular effects that exceeds the number of track intersections.

(A 30) The majority of bystander studies relate to cellular irradiation with high LET alpha particles and protons although some low LET studies, particularly on signalling through the growth medium, are available. The biological mechanisms involved in bystander signalling are probably diverse and remain to be adequately elucidated. Some data point towards induction of oxidative stress and modulation of DNA damage-response pathways. In the case of effects mediated through the culture medium, there is some evidence for the release of chromosome-damaging (clastogenic) factors from irradiated cells and the mobilisation of intracellular calcium together with increased reactive oxygen species in recipient cells.

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(A 31) Thus, the phenomena of induced genomic instability and bystander effects when expressed in vitro may show some common stress-related mechanisms. There are, however, few data and some controversies on the relative contribution of bystander signalling to cellular effects overall and the extent to which this is dose-dependent. Studies on bystander effects in vivo are in their infancy although there are some positive data relating to clastogenic factors.

A.2.6. Tissue reactions (deterministic effects)

(A 32) There have been no profound changes in scientific views on the quantitative aspects of harmful radiation-induced tissue reactions (deterministic effects) since 1990. However, there have been some developments concerning the mechanisms through which these reactions may be modified (see also Section A.3).

(A 33) An increasing number of studies on early tissue reactions have shown the ability to modify these using various cytokines and growth factors, primarily to stimulate regeneration of progenitor cells. Other biological response modifiers can be used for late reactions, in particular vascular modifying agents that delay the expression of organ damage induced in experimental animal systems. This ability to modify the response of tissues and organs means that the term 'deterministic effects' is not entirely accurate because, quantitatively, the effects are not necessarily pre-determined. Nevertheless, this term has become widely and firmly established, and the Commission continues to use the expression 'deterministic effects' to denote tissue and organ reactions.

(A 34) It has been recognised more since the 1990 Recommendations that the structure of tissues and organs plays a major role in their response to irradiation. Paired organs, or organs where the functional subunits (FSU) are arranged in parallel, rather than in series, can sustain inactivation of many FSU without clinical signs of injury, because of a substantial reserve capacity and compensation by the remainder of the FSU. This is one of the major reasons for the presence of a threshold dose for overt injury, and in particular for a high tolerance to partial-body irradiation, where a critical part of such organs may be spared.

(A 35) Late tissue reactions not only have a long and dose-dependent latency period before expression, but also they have a long progression period, with the incidence in many cases still rising well past 10 years after irradiation. Late reactions can be 'generic', which means that they arise directly in the responsible target tissue. Alternatively, late reactions can be 'consequential', meaning that they arise as a later consequence of a severe early reaction affecting the target tissue.

(A 36) There has been a consolidation of the use of the linear-quadratic formalism for describing the changes in iso-effective dose resulting from changes in the pattern of dose delivery, i.e., acute single doses, multifractionated doses, or continuous exposures. In general, the ratio of the linear and quadratic constants is higher for early reactions and consequential late reactions, and lower for generic late reactions.

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A.2.7. Mechanisms of radiation tumorigenesis

(A 37) The technical and academic developments in biology since 1990 have also had a major impact on our understanding of the complex process of multistage tumorigenic development (e.g., UNSCEAR 1993, 2000, NCRP 2001, NAS/NRC 2006, ICRP 2005d). In simple terms the complex multistage process may be subdivided in the following way: a) Tumour initiation – the entry of a normal cell into an aberrant cellular pathway (pre-neoplastic state) that can lead to cancer; b) Tumour promotion – enhancement of the growth and development of a pre-neoplastic clone of initiated cells; c) Malignant conversion – the change from a pre-neoplastic state to one where cancer development is likely; and d) Tumour progression – the later phases of tumorigenesis where cells gain properties that allow more rapid development and the acquisition of invasive characteristics.

(A 38) In brief both lympho-haemopoietic and solid tumours are believed to originate from single stem-like cells in their respective tissues. Certain gene and chromosomal mutations, which are often tissue-specific, can confer cellular properties which allow these target stem cells to partially escape from their normal constraints of growth and development. In some cases these cells acquire novel properties via gain of function mutations in so-called oncogenes; in others, it is loss of function of so-called tumour-suppressor genes that applies. On current hypotheses, the full potential for malignancy in these tumour-initiated cell clones is then developed in a step-wise fashion via the appearance of other gene/chromosomal mutations or in some cases the non-mutational silencing of key genes. In this way, over time, tumours develop increasing malignant potential by growth selection and the bypass of cell senescence. In some cases the rate of tumour development may be increased following the acquisition of mutations that result in the de-stabilisation of DNA and chromosomes. This process of accelerated mutation rate can be a major drive for tumorigenesis in many tissues but, given its clear mutational basis, tumour-associated genomic instability is distinct from the phenomenon of radiation-induced genomic instability noted in Section A.2.5.

(A 39) Tumour development is, however, far more complex than the stepwise accumulation of clonal mutations. There is good evidence that the micro environmental interaction of tumorigenic and normal cells is a critical element in cancer development, and the recruitment of a blood supply to an evolving solid tumour is one important example of this.

(A 40) Since 1990 there has been good progress in understanding the mechanistic basis of radiation tumorigenesis using animal models and by undertaking genetic analysis of certain radiation-associated human tumours (see UNSCEAR 1993, 2000, NCRP 2001, NAS/NRC 2006, ICRP 2005d).

Animal models of radiation tumorigenesis

(A 41) A combination of cellular, cytogenetic, molecular and histopathological techniques has been employed to investigate experimentally multistage radiation tumorigenesis. Much of the most informative work has been undertaken in rodent models with some of these models having a genetic basis which has been informed

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by studies with human counterpart tumours. In brief, for leukaemia and solid tumours of the skin, bone, brain, lung, breast and gastro-intestinal tract there is evidence on the process of multistage tumorigenesis after radiation and the identity of some of the critical mutations involved. Many of these mutations are present in the human counterpart tumours and also in the same rodent tumours arising spontaneously or after exposure to other carcinogens. Overall a key message from these studies is that radiation tumorigenesis appears to proceed in an unremarkable multistage manner with no obvious features that distinguish radiation as an unusual carcinogen. In particular, although data remain sparse, there are as yet no indications that the epigenetic process of induced genomic instability makes a consistent and major contribution to radiation tumorigenesis.

(A 42) Animal models have also been used to investigate the point of action of radiation in multistage tumour development (UNSCEAR, 1993, 2000, NCRP, 2001, ICRP, 2005d, NAS/NRC, 2006). These data provide evidence that radiation is only a weak promoter of tumour development and a role in the earliest (initiation) phase of tumorigenesis seems more likely. More direct evidence of such initiation properties has been obtained in a recent study of post-irradiation intestinal tumorigenesis in *Apc*-deficient mice (Ellender et al., 2005). This study showed that the principal effect of radiation was to increase the number of microscopic pre-neoplastic intestinal lesions rather than to enhance tumour development, and also that direct single-gene mutational events could account for radiation-induced intestinal adenoma yields. Molecular and cytogenetic studies using animal models add further weight to the argument that radiation acts early in the tumorigenic process via a gene-loss mechanism.

(A 43) In principle, its mutagenic properties should allow radiation to contribute throughout multistage tumorigenesis. However, the very high spontaneous rate of genome instability and damage that frequently characterises the post-initiation phases would tend to make these later phases less dependent on radiation-induced mutations (UNSCEAR 2000).

(A 44) Data from quantitative animal studies on radiation tumorigenesis are important for the development of some critical judgements in radiological protection. The implications of such data in respect of the effects of dose, dose-rate and radiation quality are noted later in this Annex.

Radiation-associated human tumours

(A 45) There are limited opportunities for mechanistic investigations with human tumours which have a high probability of radiation causation. The cytogenetic and molecular studies undertaken with radiation-associated tumours of lung, liver, thyroid, skin and bone marrow have tended to focus on particular gene or chromosomal mutations, and the relationship between these mutations and initial radiation damage remains unclear (UNSCEAR, 2000). However, in general accord with the results of animal studies, the human data developed since 1990 do not suggest that radiation tumorigenesis proceeds in an unusual fashion; evidence for the presence of specific mutational signatures of radiation is currently lacking. The involvement of induced

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genomic instability in radiation tumorigenesis has been found to be lacking or is viewed as controversial (Nakanishi et al., 2001, Cox and Edwards, 2002, Lohrer et al., 2001).

Genetic susceptibility to cancer

(A 46) The issue of inter-individual genetic differences in susceptibility to radiation-induced cancer was noted in *Publication 60* and reviewed in *Publication 79* (ICRP 1998a), UNSCEAR (2000, 2001) and the BEIR VII report (NAS/NRC 2006). Since 1990 there has been a remarkable expansion in knowledge of the various single-gene human genetic disorders where excess spontaneous cancer is expressed in a high proportion of gene carriers – the so-called high penetrance genes. There is also a growing recognition and some data on variant genes of lower penetrance where gene–gene and gene–environment interactions determine a far more variable expression of cancer.

(A 47) Studies with cultured human cells and genetically altered laboratory rodents have also contributed much to knowledge and, with more limited epidemiological/clinical data, suggest that a high proportion of single-gene, cancer-prone disorders will show increased sensitivity to the tumorigenic effects of radiation.

(A 48) Recently, good progress has been made in demonstrating experimentally the complex interactions that may underlie the expression of cancer-predisposing genes of lower penetrance (NAS/NRC 2006); this work is however in its infancy.

A.2.8. Heritable diseases

(A 49) Views on the risks of induction of heritable diseases by radiation exposure of the gonads were developed in *Publication 60* (ICRP, 1991b) by extrapolating quantitative data on dose response for germ cell mutations in experimental animals (predominantly mice) to humans. Although extended follow-ups of mortality and cancer incidence in the offspring of the Japanese A-bomb survivors have been published (Izumi et al., 2003a, 2003b) these data do not alter the conclusions of previous analyses. In addition, few new quantitative data on mutation induction in mice have become available. However, since 1990 there have been significant developments in our understanding of the mutational process and new concepts for genetic risk estimation in human populations (UNSCEAR 2001, NAS/NRC, 2006). Although it remains the case that no human studies provide direct evidence of a radiation-associated excess of heritable disease, the data from experimental animals provide a compelling reason for ICRP to continue to make best use of advances in genetics in order to improve its estimate of these risks.

(A 50) The application of molecular genetic techniques has provided detailed knowledge of the molecular basis of naturally occurring mutations that cause heritable diseases in humans; also of radiation-induced gene (specific locus) mutations in mouse germ cells. There is now strong evidence that large multilocus deletions of the genome constitute the predominant class of radiation-induced mutation. It is judged that only a proportion of such multigene loss events will be compatible with

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embryonic/fetal developmental and live birth. These findings have led to the concept that the principal adverse genetic effect in humans is likely to take the form of multisystem developmental abnormalities rather than single gene diseases.

(A 51) Another conceptual change based upon new human genetic information is the development of methods to assess the responsiveness of the frequency of chronic multifactorial diseases (e.g., coronary heart disease and diabetes) to an increase in mutation rate. This has allowed an improved estimate to be made of the risks associated with this large and complex class of disease where expression requires the interaction of genetic and environmental factors.

(A 52) These human genetic, experimental and conceptual advances have been integrated to form a new and more robust framework for the estimation of genetic risks (UNSCEAR 2001).

(A 53) There have also been developments on the estimation of radiation-induced mutation rates in mice and humans using expanded simple tandem DNA repeat (ESTR) loci in mice and minisatellite loci in humans. These DNA repeats are highly mutable with the mutations manifesting as changes in the number of tandem repeats. This increased mutability is expressed spontaneously and after radiation, and attention has been given to the mutational mechanisms involved, including the untargeted and transgenerational effects of radiation (UNSCEAR, 2000, 2001, CERRIE, 2004). However, since on current knowledge mutations at these DNA repeat sequences are only rarely associated with genetic disorders, the Commission judges that there is no good reason to include quantitative mutational data for these loci in the estimates of genetic risk given in Section A.6 of this report.

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A.3. Risks of tissue reactions (deterministic effects)

A.3.1. Revision of judgements given in ICRP *Publication 60*

Definition of stochastic effects and tissue reactions

(A 54) The deposition of energy by ionising radiation is a random process. Even at very low doses it is possible that sufficient energy may be deposited into a critical volume within a cell to result in cellular changes or cell death. The killing of one or a small number of cells will, in most cases, have no consequences in tissues, but modifications in single cells, such as genetic changes or transformations leading ultimately to malignancy, may have serious consequences. These effects resulting from damage in a single cell are termed stochastic effects. There is a finite probability of the occurrence of such stochastic events even at very low doses, so there will be no threshold dose unless all such events can be repaired up to some level of dose. As the dose is increased the frequency of such events increases, but in the absence of other modifying factors, the severity of the resultant effects is not expected to increase, in contrast to the case for tissue reactions (see below).

(A 55) With larger doses there may be a substantial amount of cell killing, sufficient to result in detectable tissue reactions. These reactions may occur early or late after irradiation. The depletion of renewing parenchymal cell populations, modified by stromal influences, plays a crucial role in the pathogenesis of early tissue reactions. In order to reach the level of detection, a given proportion of cells must be depleted. This constitutes a threshold, which depends on the specified level of injury. These reactions are distinct from the stochastic effects in single cells, which are the induction of cancers from irradiated somatic cells and genetic diseases in offspring following parental germ cell irradiation.

(A 56) When the term stochastic was introduced regarding single-cell effects, effects caused by injury in populations of cells were called non-stochastic (*Publication 41*, ICRP 1984). This was later considered an unsuitable term, and in *Publication 60* (ICRP 1991b) it was replaced by the term deterministic, meaning 'causally determined by preceding events'. Now it is recognised that both early and late tissue reactions are not necessarily predetermined, and they can be modified after irradiation by the use of various biological response modifiers. Hence it is considered more accurate to refer to these effects as early or late tissue or organ reactions. However, the Commission recognises that the generic terms, deterministic and stochastic effects, have a firmly embedded use in its system of protection and will use the generic and directly descriptive terms synonymously, according to context.

Tissue and organ reactions

(A 57) Early tissue reactions (on a timescale of hours to a few weeks) can be inflammatory-type reactions as a result of cell permeability changes and histamine release, e.g., erythema, and subsequent reactions as a consequence of cell loss, e.g., mucositis, and desquamatory reactions in epithelial tissues.

(A 58) Late tissue reactions (on a timescale of months to years) are called 'generic' if they occur as a result of injury directly in the target tissue, e.g., vascular occlusions

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leading to deep tissue necrosis after protracted irradiations, or 'consequential' if they occur as a result of early reactions, e.g., dermal necrosis as a result of severe epidermal denudation and chronic infection, and intestinal strictures caused by severe mucosal ulceration (Dörr and Hendry 2001).

Cell survival curves

(A 59) Cell depletion plays a major role in the early desquamatory reactions in epithelial tissues after irradiation. In a few cell types and tissues, rapid cell loss after irradiation is mediated by apoptosis, as exemplified by lymphocytes and salivary glands. In other tissues, cell death is caused by reproductive failure of regenerative stem cells, which may undergo apoptosis before or after attempted mitoses, or of proliferating transit (differentiating) cells. The majority of non-proliferating mature cells do not die from irradiation, but from natural senescence. For a given level of tissue damage, it has been shown that dose modifying factors for different irradiation conditions are the same for survival of tissue target cells and for a given level of early tissue reactions, demonstrating the importance of target cell survival for these types of reaction (Hendry and Thames 1987).

(A 60) The survival of cells as a function of dose (Fig. A.3.1) is commonly described using the linear-quadratic equation:

$$S = \exp -(\alpha D + \beta D^2)$$

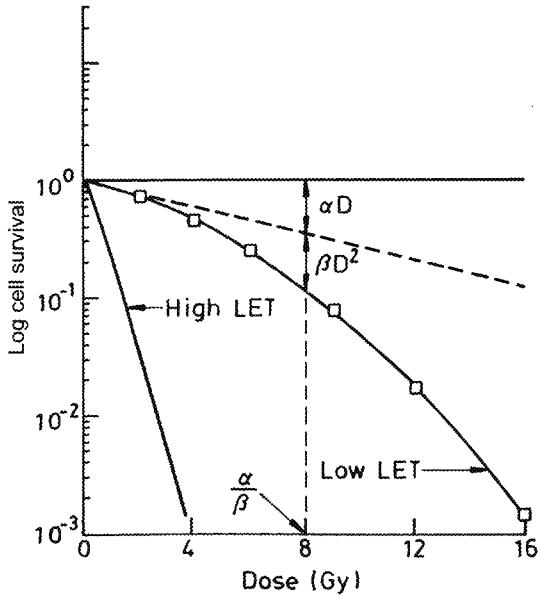

Fig. A.3.1. Dose response for cell survival (S) on a semi-log plot described by the linear-quadratic equation $S = \exp - (\alpha D + \beta D^2)$. From ICRP (1991b).

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(A 61) The constant α describes the linear component of cell sensitivity to killing on a semi-log plot of survival (log) versus dose (linear), and β describes the increasing sensitivity of cells to higher radiation doses. The ratio α/β is the dose at which the linear and quadratic components of cell killing are equal. This ratio is a measure of the curvature of the survival curve. The α/β ratio is lower and the curve on a semi-log plot is more pronounced for homogeneous, slowly proliferating cell populations, such as in slow-renewing organ systems such as kidney and spinal cord. The α/β ratio is higher and the survival curve is straighter for heterogeneous, rapidly proliferating cell populations, such as the regenerative target cell populations in oral mucosa and intestine. One possible contributor to this straightening is the presence of sub-populations with different sensitivities as a function of cell-cycle phase. The α/β ratio is generally in the range 7–20 Gy for early reactions in tissues (10 Gy is commonly used) and 0.5–6 Gy for late reactions (3 Gy is commonly used).

(A 62) When dose rates are lower than around 0.1 Gy/hour there is repair of cellular radiation injury during the irradiation. This causes the β component to decrease and to reach zero at very low dose rates. The α component is not modifiable by changing dose rate. A special feature for some cell types is hypersensitivity to doses less than 0.5 Gy, typically at 0.2–0.3 Gy (Joiner et al. 2001), but not at higher doses. This causes a deviation from the smooth linear-quadratic cell survival curve. It is considered by some to be due to stimulation of repair processes at doses above 0.2–0.3 Gy. The deviation has been detected for early skin reactions in humans, and for skin reactions and kidney injury in experimental animal systems. The relevance of this hypersensitivity phenomenon for tissue injury thresholds is not yet clear.

(A 63) With high LET irradiations, there is less repairable injury and hence the β component and dose rate effects are small or absent. There is also no hypersensitivity component to the survival curve.

Early and late reactions in tissues and organs

(A 64) Early desquamatory reactions in epithelia, and depression of the haemopoietic system, are caused by the sterilisation of stem and progenitor cells in the tissues, resulting in a transitory or permanent lack of mature cells depending on the level of dose. Such reactions are characteristic of the radiation response of renewing cell lineages, such as those of the epidermis, mucosa, haemopoiesis and spermatogenesis. The time course of expression and restoration of tissue components generally depends on their normal rate of renewal, and is dose dependent at low doses but not at high doses. Complete denudation of such tissues after high doses occurs at a time equivalent to the lifetime of new mature cells plus those produced by any radioresistant progenitor cells. The stroma produces a variety of growth factors that induce the repopulation and differentiation needed to restore particular tissue components. The time course can be advanced and the restoration made more complete by the application of exogenous growth factors that further stimulate the reparative processes.

(A 65) Late reactions in tissues are due in part to the slow rate of renewal and death of component cell populations, where the cells are functional as well as capable

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of division (Michalowski 1981, Wheldon et al. 1982). Late reactions are also due to dysfunction of a complex system of inter-cellular signalling pathways which normally regulate the various tissue and organ functions (Rubin et al. 1998). In some tissues it has been shown that different types of damage appear after different latency periods. For example, in spinal cord, there is an early demyelination effect within a few months, then a second phase of demyelination and necrosis of the white matter after 6–18 months, and a later phase after 1–4 years that is mostly a vasculopathy (van der Kogel 2002).

(A 66) In most tissues, responses are greater when irradiated volumes are larger. With early skin reactions, the volume effect is due largely to the decreasing ability to heal large areas mainly because of limited cell migration from the margins. With late reactions the volume effect relates to organ architecture. In spinal cord the critical elements are arranged in series, so that when more elements are irradiated, there is a greater chance of inactivating one of them to cause paralysis. There is also less benefit from cellular migration from the edges of the radiation field when irradiated volumes are larger. By contrast, in for example kidney and lung, the tissue functional subunits (FSU, respectively nephrons and alveoli) are arranged in parallel (Withers et al. 1988). In these cases, there can be inactivation of some FSU without causing a decrease in organ function, until a critical number of FSU is reached. Late tissue injury is progressive and strongly dose dependent, and it has been shown that the incidence of late morbidity after radiotherapy in humans continues to increase gradually to 10 years and beyond (Jung et al. 2001). There are various procedures that have been shown in experimental animal systems to delay the onset and development of late radiation morbidity (see below).

(A 67) Tissues vary not only in their temporal responsiveness, but also in their radiosensitivity. Among the most radiosensitive tissues are the ovary and testes, bone marrow, and the lens of the eye. In general, the dose-incidence relationship for these tissues will be sigmoid in shape when plotted on linear axes, the effect becoming more frequent as the dose increases (Fig. A.3.2a). Tissue and organ reactions vary with the dose, in severity as well as in incidence. The upper panel in Fig. A.3.3 illustrates how the incidence of a particular reaction, defined as a clinically recognisable pathological condition, increases as a function of dose in a population of individuals of

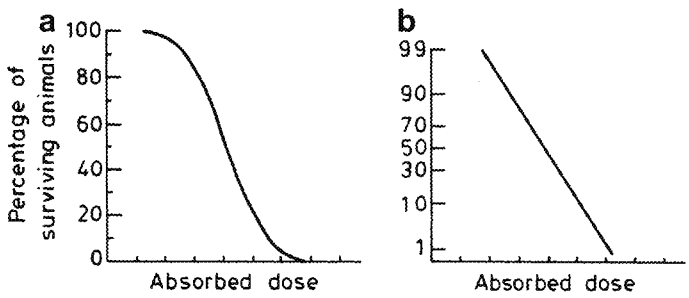

Fig. A.3.2. Relationship between mortality and dose: (a) sigmoid relationship on a linear–linear plot, (b) linear relationship on a transformed-probability–linear plot. From ICRP (1991b).

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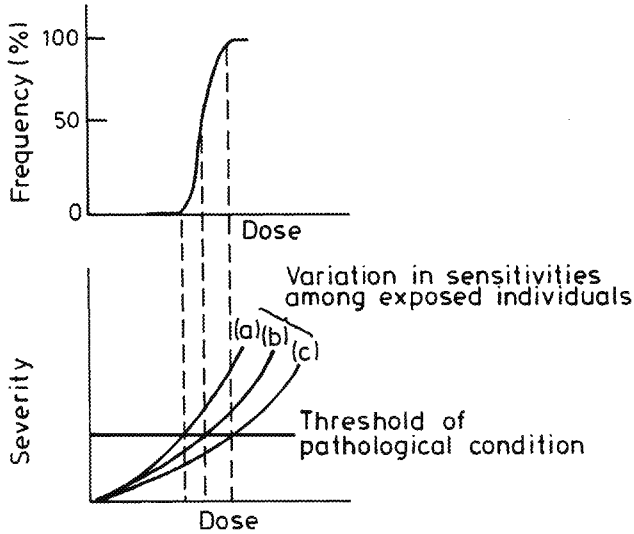

Fig. A.3.3. Relationships between dose and the frequency and severity of tissue reactions (deterministic effects). Upper panel: expected sigmoidal increase in frequency in a population of individuals with varying sensitivities. Lower panel: expected dose-severity relationships for three individuals with different sensitivities. From ICRP (1991b).

varying sensitivities. The lower panel in Fig. A.3.3 represents the dose-severity relationship for a population of individuals with various sensitivities. The severity of the pathological condition increases most markedly in those individuals in a subgroup who are most sensitive (curve a), reaching the threshold of detectability at a lower dose than in the less sensitive groups (curves b and c). The range of dose over which the different subgroups cross the same threshold of severity is reflected in the upper panel of Fig. A.3.3, which shows the frequency of the pathological condition in the total population, and which reaches 100% only at that dose which is sufficient to exceed the defined threshold of severity in all members of the population.

(A 68) In reality, substantially less than 1% of a general population is very radiosensitive because of inherited mutations in important DNA damage-sensing or repair genes. The remainder has a spectrum of sensitivities, and this has a flattening influence on the slope of the dose-incidence curve. This modification of the slope is in addition to primary contributions from inherent target-cell sensitivity and from features of tissue architecture discussed above. It is not yet possible to determine accurately the sensitivity of individuals within this spectrum of radiosensitivities, using cellular or molecular tests.

(A 69) Threshold doses for some tissue and organ reactions in the more radiosensitive tissues in the body are shown in Table A.3.1. These have been deduced from various radiotherapeutic experiences and accidental exposure incidents. In general, fractionated doses or protracted doses at low dose rate are less damaging than are acute doses.

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Table A.3.1. Estimates of the thresholds for tissue effects in the adult human testes, ovaries, lens, and bone marrow (from ICRP 1984, *Publication 41*[1]).

Tissue and effect	Threshold		
	Total dose received in a single brief exposure (Gy)	Total dose received in highly fractionated or protracted exposures (Gy)	Annual dose rate if received yearly in highly fractionated or protracted exposures for many years (Gy y^{-1})
Testes			
Temporary sterility	0.15	NA[2]	0.4
Permanent sterility	3.5–6.0[3]	NA	2.0
Ovaries			
Sterility	2.5–6.0	6.0	>0.2
Lens			
Detectable opacities	0.5–2.0[4]	5	>0.1
Visual impairment (Cataract)[5]	5.0[5]	>8	>0.15
Bone marrow			
Depression of hematopoiesis	0.5	NA	>0.4

See Table A.3.4 and Section A.3.1.7 for revised judgements.

[1] For further details consult *Publication 41* (ICRP 1984).

[2] NA denotes Not Applicable, since the threshold is dependent on dose rate rather than on total dose.

[3] See UNSCEAR (1988).

[4] See also Otake and Schull (1990).

[5] Given as 2–10 Sv (NCRP 1989) for acute dose threshold.

Mortality after whole body exposure

(A 70) Mortality after irradiation is generally the result of severe cell depletion in tissues of, or other major dysfunction of, one or more vital organs of the body. After partial body irradiation, or inhomogeneous whole body irradiation, the probability of death of an individual will depend on the particular organs exposed, the volume irradiated, and the dosage level. After whole body irradiation which is fairly homogeneous, for example with penetrating photon beams above about 1 MeV energy, death may occur from one of several distinct syndromes which are characteristic of particular dose ranges, and which are due to injury in specific organ systems.

(A 71) For a specific syndrome potentially leading to death, the relationship between the percentage of survivors and the dose is sigmoid in shape on a linear plot, whereas for a transformed probability-linear plot the shape is approximately linear (Fig. A.3.2b). The survival–dose relationship is often described by its midpoint, the LD_{50}, i.e., the dose that is lethal for half of the individuals, and the slope of the curve. The slope can be characterised by the probit width, which is the standard deviation of the distribution, or by other parameters in other transformations of the data. Values of $LD_{5\text{-}10}$ and $LD_{90\text{-}95}$ are helpful in assessments of the dose that will result in the death of only a few or of many.

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(A 72) For a normal healthy adult human, the $LD_{50/60}$, i.e., within 60 days, is around 4 Gy midline dose, but there are estimates in the literature ranging from 3 to 5 Gy. Estimates of LD_{10} are around 1–2 Gy, and around 5–7 Gy for LD_{90} (UNSCEAR, 1988 Annex G, NUREG, 1997). The cause of death is haemopoietic failure, resulting primarily from a lack of progenitor cells that produce functional short-lived granulocytes, as well as from haemorrhages without the replacement of radioresistant red cells. It is possible to improve the chances of survival of individuals exposed to doses around or even above the $LD_{50/60}$ by appropriate medical care such as fluid replacement, antibiotics, antifungal drugs, and barrier nursing (UNSCEAR, 1988 Annex G), by infusing platelets and concentrates of isologous blood stem cells, and by injecting growth factors such as granulocyte-macrophage colony-stimulating factor. Some experts have considered that supportive medical treatment may increase the $LD_{50/60}$ to around 5 Gy, and possibly to around 6 Gy if growth factors are also employed (NUREG, 1997). In experimental animal systems these procedures have been shown to significantly increase the LD_{50} values (Table A.3.2). Growth factors have been used for many years in the treatment of humans following whole body irradiation for haematological diseases. However, in the few cases of accidental radiation exposures where they have been used, they did not save the individuals who were considered at risk of death, possibly because of the delay in starting treatment. Although the growth factors were considered to be of some benefit in the early post-exposure period, treated individuals died from organ reactions such as pneumonitis.

(A 73) At doses in excess of about 5 Gy, additional effects occur, including severe gastrointestinal (stem cell and endothelial capillary cell) damage which, when combined with haemopoietic damage, causes death in 1–2 weeks. There are few human data to assess accurately the LD_{50} for this syndrome, but it may be approaching 10 Gy acute dose (UNSCEAR, 1988 Annex G, NUREG, 1997), and supportive medical treatment and growth factors are expected to increase this approximate value. If some marrow and most of the gut have been spared because of inhomogeneous irradiation, then at acute doses above 10 Gy to the lungs, acute inflammation (pneumonitis) may occur leading to death. Renal damage also occurs in the same dose range, if the kidneys have been irradiated. All these effects potentially can be alleviated to some extent, as evidenced by the success of growth factors and other molecules in reducing tissue and organ injury in animal systems after irradiation (Table A.3.2). At even higher doses towards 50 Gy and above, there is acute damage in the nervous and cardiovascular systems and the individual dies of shock after a few days (NCRP, 1974). Approximate doses for death at different times are given in Table A.3.3. These are for high dose, low LET radiation given over a few minutes.

(A 74) If the dose is given over a period of hours or more it requires a greater whole body dose for these effects to occur. For example, if the dose rate is about 0.2 Gy per hour, LD_{50} values may be increased by around 50% (NUREG, 1997). If the dose is delivered over a month, the $LD_{50/60}$ may be doubled (UNSCEAR, 1988 Annex G). At low (chronic) radiation dose rates, there is evidence of a chronic radiation syndrome affecting in particular the haemopoietic, immune and neural systems (Guskova et al., 2002, AFRRI, 1994, 1998, Akleyev and Kisselyov, 2002). The threshold doses for depression of the immune system is about 0.3–0.5 Gy per year

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Table A.3.2. Dose-modifying factors (DMF) reported in mice or other species where stated. Updated from Hendry (1994).

Organ	Agent	DMF[a]
Bone marrow:		
Early reactions	Antibiotics Granulocyte-macrophage Colony-stimulating-factor	1.2–1.8 (rodents and monkeys)
Intestine:		
Early reactions	Antibiotics	1.1–1.4 (rats)
	Interleukin–1	1.1
	Angiogenic growth factors	1.1 (mice)[b]
	Interleukin–11, Transforming growth factor-β3	>1.0
Late reactions	Low molecular weight diet	>1.0 (rats)
	Antiplatelet Clopidogrel	>1.0 (rats)[c]
Skin:		
Alopecia	Prostaglandin E2	1.2–1.5
Early reactions	γ-linolenic acid	1.1–1.2 (pigs)
Late reactions	γ-linolenic acid	1.1–1.2 (pigs)
	Blood-cell modifiers	1.4
	Cu/Zn/Mn-SOD	>1.0 (pigs)[d]
Oral mucosa:		
Early reactions	Keratinocyte growth factor	about 2.0
Lung:		
Pneumonitis	Interleukin–1,	>1.0
	Tumour necrosis factor-α	>1.0
Spinal cord:		
Late reactions	Vasoactive agents	1.1 (rats)
Kidney:		
Late reactions	Captopril, angiotensin II blockers	>1.0 (rats)

[a] DMF = ratio of radiation doses with or without the protective agent, causing the same level of effect.

>1.0 indicates that the observed protection could not be quantified in terms of a DMF value, because dose-response relationships were not available. Reactions were assessed as less severe for combined radiation and agent.

[b] Okunieff et al. (1998).

[c] Wang et al. (2002).

[d] Lefaix et al. (1996).

(Akleyev et al., 1999), and estimated threshold doses for effects in other organs are given in Table A.3.1. Severe reactions do not occur in most body tissues of adults or children after annual doses below 0.1 Gy over many years. Red bone marrow, reproductive cells, and the lens of the eye show the greatest sensitivity.

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Table A.3.3. Range of doses associated with specific radiation-induced syndromes and death in human beings exposed to acute low LET uniform whole body radiation.

Whole body absorbed dose[a] (Gy)	Principal effect contributing to death	Time of death after exposure (days)
3–5	Damage to bone marrow ($LD_{50/60}$)	30–60
5–15	Damage to the gastrointestinal tract	7–20
5–15	Damage to the lungs and kidney	60–150
>15	Damage to nervous system	<5, dose-dependent

[a] Some dose range data include judgements from outcomes of partial body irradiations.

(A 75) Tissue and organ reactions resulting from exposure to high LET irradiation are similar to those from low LET exposure, but their frequency and severity are greater per unit absorbed dose of high LET irradiation. These differences are expressed in terms of the relative biological effectiveness (RBE) for the effect under consideration. The RBE of high versus low LET radiation is defined as the ratio of absorbed doses of the reference low LET radiation and the high LET radiation that result in the same level of biological effect.

(A 76) RBE values for tissue and organ reactions are higher at lower doses and also when low doses per fraction are given repeatedly to accumulate the total dose (*Publication 58*, ICRP 1989b). RBE values tend to be smaller for early effects in haemopoietic and reproductive tissue, larger for gastrointestinal tract and skin, and even larger for late reactions in, for example, lung and kidney.

(A 77) The effective maximum RBE will be that value which applies at the threshold dose for the particular effect under consideration. This will be less than the value RBE_M, which is defined as the ratio of such doses at very low doses. This is the ratio of the linear components of the linear-quadratic fittings to data at higher doses. Hence it represents an extrapolation to dose levels below the threshold dose, which is of theoretical but not of practical interest. It also ignores the possibility of occult hypersensitivity at very low doses (see Section 3.1, paragraphs (A 59)–(A 63). RBE_M values for neutrons are 2–5 times lower, and effective maximum RBE values are even lower than values of RBE_M for stochastic effects in corresponding tissues. Thus the use of Q or w_R values in cases where tissue effects are over-riding would result in an overestimate of the contribution to the risk from high LET radiation.

Summary of projected estimates of dose thresholds for morbidity and mortality

(A 78) For the purposes of developing judgements for the present ICRP Recommendations, the Commission decided to update and summarise threshold estimates of the acute absorbed doses for 1% incidences of morbidity and mortality involving adult human organs and tissues after whole body gamma ray exposures. These 1% incidence estimates, derived from publications which utilise mathematical

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Table A.3.4. Projected threshold estimates of the acute absorbed doses for 1% incidences of morbidity and mortality involving adult human organs and tissues after whole body gamma ray exposures.

Effect	Organ/tissue	Time to develop effect	Absorbed dose (Gy)[e]
Morbidity:			*1% Incidence*
Temporary sterility	Testes	3–9 weeks	~0.1[a,b]
Permanent sterility	Testes	3 weeks	~6[a,b]
Permanent sterility	Ovaries	< 1week	~3[a,b]
Depression of blood-forming process	Bone marrow	3–7 days	~0.5[a,b]
Main phase of skin reddening	Skin (large areas)	1–4 weeks	<3–6[b]
Skin burns	Skin (large areas)	2–3 weeks	5–10[b]
Temporary hair loss	Skin	2–3 weeks	~4[b]
Cataract (visual impairment)	Eye	Several years	~1.5[a,c]
Mortality:			
Bone marrow syndrome:			
– without medical care	Bone marrow	30–60 days	~1[b]
– with good medical care	Bone marrow	30–60 days	2–3[b,d]
Gastro-intestinal syndrome:			
– without medical care	Small intestine	6–9 days	~6[d]
– with good medical care	Small intestine	6–9 days	>6[b,c,d]
Pneumonitis	Lung	1–7 months	6[b,c,d]

[a] ICRP (1984).
[b] UNSCEAR (1988).
[c] Edwards and Lloyd (1996).
[d] Scott and Hahn (1989), Scott (1993).
[e] Most values rounded to the nearest Gy; ranges indicate area dependence for skin and differing medical support for bone marrow.

projections of dose-response data, are given in Table A.3.4, together with estimates of development times for the effects in question.

Dose limits for specific tissues

(A 79) *Publication 60* (ICRP 1991b, paragraph 194 and Table 6) describes the need to provide dose limits for exposure of the eye and localised areas of the skin because these tissues are not necessarily protected against radiation-induced reaction/injury by the limit on effective dose which, in these circumstances, protects against cancer development.

(A 80) Information available since 1990 has not provided evidence necessitating a change of view of the tumorigenic radiosensitivity of the skin or relevant subcutaneous tissues. It is judged therefore that the occupational and public dose limits for the skin and hands/feet given in Table 6 of *Publication 60* remain applicable. However, recent studies have suggested that the lens of the eye may be more radiosensitive than previously considered. In particular, among both A-bomb survivors (Minamoto et al., 2004) and a group of children treated for skin haemangioma (Hall et al., 1999), there is evidence of excesses of both cortical and posterior subcapsular cataract at doses somewhat lower than expected. In the assignment of a dose threshold for cataract, uncertainties are recognised on the mechanisms of cataract development, and

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also on the relationship between the detection of lens opacity and the expression of visual impairment. The recent data and mechanistic uncertainties noted above highlight the need for a detailed reappraisal of the radiosensitivity of the lens of the eye and a newly formed Task Group of ICRP Committee 1 will address this issue.

A.3.2. Effects in the embryo and fetus

(A 81) The risks of tissue injury and developmental changes (including malformations) in the irradiated embryo and fetus have been reviewed recently in *Publication 90* (ICRP, 2003a). In the main, this review reinforced the judgements on in-utero risks given in *Publication 60* (ICRP, 1991b) although, on some issues, new data allow for clarification of views. On the basis of *Publication 90*, the following conclusions can be summarised on the in-utero risks of tissue injury and malformation at doses up to a few tens of mGy low LET.

(A 82) The new data from animal studies confirm embryonic sensitivity to the lethal effects of irradiation in the pre-implantation period of embryonic developments. At doses of a few tens of mGy such lethal effects will be very infrequent, and the data reviewed provide no reason to believe that there will be significant risks to health expressed after birth.

(A 83) In respect of the induction of malformations, the animal data strengthen the view that there are gestation age-dependent patterns of in-utero radiosensitivity with maximum sensitivity being expressed during the period of major organogenesis. On the basis of these animal data it is judged that there is a dose threshold of around 100 mGy for the induction of malformations; therefore, for practical purposes, risks of malformation after low-dose in-utero exposure may be discounted. *Publication 90* (ICRP 2003a) reviews the experimental data on neurodevelopment following in-utero irradiation for which dose thresholds generally apply; it also considers human epidemiological data as summarised below.

(A 84) The review of human A-bomb data on the induction of severe mental retardation after irradiation in the most sensitive prenatal period (8–15 weeks post conception) now more clearly supports a dose threshold of at least 300 mGy for this effect and therefore the absence of risk at low doses. The associated data on IQ losses estimated at around 25 points per Gy are more difficult to interpret and their significance is unclear. Although a non-threshold dose response cannot be excluded, even in the absence of a true dose threshold, any effects on IQ following in-utero doses of a few tens of mGy would be of no practical significance for the vast majority of individuals. This judgement accords with that developed in *Publication 60* (ICRP, 1991b).

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A.4. Risks of radiation-induced cancer

(A 85) In the development of judgements on the risk of radiation-induced cancer in the dose range up to around 100 mSv, the Commission has given attention to: a) the implications of fundamental data on radiation response; b) quantitative aspects of animal tumorigenesis; and c) direct epidemiological observation of cancer risk in humans, albeit at doses generally greater than 100 mSv. The conclusions reached by the Commission on the implications of fundamental and animal data are used: i) to guide the projection of higher dose epidemiological data for the purposes of estimating cancer risk in the low dose region of interest; and ii) to consider the application of a dose and dose rate effectiveness factor (DDREF) that would apply to human exposures at low doses and low dose rates. Judgements developed in Section A.6 on heritable effects are brought forward in order to provide new estimates of detriment and the nominal risk coefficients for risk in a single section of the Annex.

A.4.1. Fundamental data on radiation response

(A 86) In formulating Recommendations for protecting humans against the tumorigenic effects of radiation, the Commission is required to consider a very broad span of biological data and concepts; many of these are subject to ongoing debate and, in some cases, contention. There is, however, general agreement that epidemiological methods used for the estimation of cancer risk do not have the power to directly reveal cancer risks in the dose range up to around 100 mSv. Accordingly there is a growing role for biological data in the development of ICRP Recommendations and, where there is uncertainty and/or contention, there is a need to arrive at a scientifically balanced judgement based upon peer-reviewed data.

(A 87) The principal criteria used by the Commission in seeking a balanced view of biological data are captured in the questions given below.

- How relevant to in-vivo human tumorigenesis are the radiobiological end-points in question?
- Is the design, methodology and statistical strength of a given study sufficient to support the published conclusions?
- Do these published conclusions accord with those of similar studies and take adequate account of other relevant experimental data?

Where there are conflicting data and concepts:

- Which of the conflicting elements show greatest coherence with fundamental knowledge of the cancer process in general and, where possible, with epidemiological data?
- How critical is the issue for the broad purposes of radiological protection?

(A 88) These questions have been applied to a large set of published cancer-related fundamental data considered by ICRP Committee 1 and by other committees with interests in radiation cancer risk (e.g., UNSCEAR 2000, NCRP 2001, NAS/NRC

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2006, ICRP 2005d). From this evaluation the following judgements have been developed by the Commission.

Dose-response relationships for gene and chromosomal mutations

(A 89) On the basis that the induction, by radiation, of gene and chromosomal mutations is of direct importance to the cancer process, the majority of relevant data from cellular studies is compatible with a simple relationship between dose and effect. A linear-quadratic form generally describes the full dose response for low LET radiations. The most informative data, although sparse, suggest linearity down to doses of a few tens of mGy, and there is no good reason to suggest a departure from this simple proportionality in the dose range down to a few mGy. At low LET radiation doses of a few mGy and below, linearity of response for targeted events in cells is expected because the fluence of tracks becomes equal to or less than the number of cells in the radiation field (see Section A.2.1). If, however, bystander effects were to be shown to contribute substantially to low-dose cellular effects in general then this expectation might not be met.

DNA damage response in cells

(A 90) There is much data to support the view that the activity of DNA damage response processes in cells is closely coupled with both cellular radiobiological effects and cancer development. On this basis the fidelity of post-irradiation DNA repair is expected to be a critical determinant of low-dose response. Current data point towards the predominance of an inherently error-prone repair process for the chemically complex DNA double-strand lesions that are characteristic of radiation action. Error-prone DNA repair at doses down to a few tens of mGy is consistent with the approximate linearity of cellular dose response for gene/chromosomal mutations and implies a simple proportionality between dose and the cancer risk associated with such mutations. The possibility of biochemical changes in DNA repair fidelity at doses below a few tens of mGy cannot be excluded but there are no specific reasons to predict such changes.

(A 91) A challenge to this conventional scientific view has come from proposals based upon the capacity of cells to sustain and repair a relatively high flux of spontaneously arising oxidative damage to DNA (see UNSCEAR 2000, NAS/NRC 2006, ICRP 2005d). The issue raised is that if cells can deal adequately with this relatively high level of spontaneous DNA damage then a small number of additional DNA lesions resulting from exposure to a few tens of mGy ($\sim$ 2 DNA double-strand lesions or $\sim$1 complex cluster per cell at $\sim$ 50 mGy low LET) would be of little or no consequence for cancer risk.

(A 92) This challenge might have some strength if spontaneously arising and radiation-induced DNA lesions were of the same type. However, as noted in Sections A.2.1 and A.2.3, there is good reason to believe that the clustered and chemically complex DNA lesions characteristic of radiation action arise very infrequently from spontaneous oxidative processes in cells; these oxidative processes tend to result in simple and readily repairable damage to the single strands of DNA. Since complex

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DNA lesions are inherently difficult to repair correctly, the challenging argument loses much of its scientific strength.

(A 93) These issues have been addressed in detail by UNSCEAR (2000), NAS/NRC (2006) and ICRP (2005d) and, for the reasons summarised above, the Commission concludes that the balance of evidence weighs against challenges to simple proportionality in low-dose response that is based upon the relative abundances of spontaneous and radiation-induced DNA damage.

(A 94) It has also been proposed that simple proportionality between dose and radiobiological effect may not apply in all circumstances because of the activity of the adaptive DNA damage-response processes noted in Section A.2.3. The Commission recognises that the data on adaptive responses in human lymphocytes is reasonably reproducible but even these data show that this form of response is not consistently expressed in cell strains and has a poorly understood mechanistic basis. Other forms of adaptive response, e.g., immunological stimulation, considered by UNSCEAR (1994, 2000), and that were seen in some recent animal studies on tumorigenesis (Mitchel et al., 1999, 2003), are also judged to have most uncertain biological bases.

(A 95) Similar conclusions have been drawn by the BEIR VII Committee (NAS/NRC, 2006). The Commission does, however, recognise that the dose-dependence of post-irradiation cellular signalling and its potential implications for DNA damage response and cancer risk is an area where more information is needed. A report from the French Academies (2005) emphasises the potential importance of such cellular signalling and cites other data to support arguments in favour of a practical threshold for low-dose cancer risk (see also Section A.4.4, paragraphs A 178–A 187).

(A 96) Overall, the Commission concludes that the concept of adaptive responses to radiation lacks adequate biological support, and the available data fail to provide good evidence of robust adaptive and protective effects for cancer. The integration of the concept of adaptive response into a biological framework for radiological protection is therefore judged to be unjustified at this time.

Epigenetic responses to radiation

(A 97) Although the Commission is well aware that research is proceeding at a good pace, the available data do not provide good evidence of a robust causal association between cancer risk and the epigenetic phenomena of induced genomic instability and bystander signalling. It seems likely that diverse stress-related cellular processes underlie the expression of both types of response, but there is much uncertainty on dose-response characteristics, the extent to which in-vivo expression occurs, and how this might influence cancer risk. On this basis, the Commission suggests that, at present, it is not possible to meaningfully integrate data on these processes into the low-dose judgements necessary for radiological protection. Indeed, since direct human epidemiological data at low LET doses of above around 100 mGy provide the principal means for estimating nominal cancer risk coefficients, at these doses cancer risk estimates will incorporate all relevant biological processes including the epigenetic factors noted in this Annex. The critical issue of uncertainty

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is therefore not simply whether such epigenetic factors influence cancer risk per se but rather whether the in-vivo dose response characteristics might provide for differential contributions to risk at, say, 200 mSv compared with, say, 10 mSv. The BEIR VII (NAS/NRC, 2006) and CERRIE (2004) Committees have also commented on the uncertain contribution of these epigenetic processes to radiation tumour risk.

A.4.2. Animal data on tumour induction and life shortening

(A 98) Animal data, largely from rodent studies, were included in consideration of relative biological effectiveness (RBE) in *Publication 92* (ICRP, 2003c) and have been reviewed in *Publication 99* (ICRP, 2005d) in respect of dose response and judgements on the dose and dose-rate effectiveness factor (DDREF). The relationship between RBE and radiation weighting (w_R) is adequately summarised in *Publication 92* and further developed in *Publication 99*.

(A 99) In respect of dose response, the most reliable animal data are generally compatible with a simple proportionate relationship between dose and risk but there are examples of highly curvilinear threshold-like responses for the induction of thymic lymphoma and ovarian cancer in mice. The processes that underlie the induction of these tumour types have a high degree of dependence upon cell killing and, for this reason, these responses are judged by the Commission to be atypical (see ICRP 2005d).

(A 100) When mouse data for thymic lymphoma and ovarian cancers are excluded from analyses the values for DDREF from animal studies are generally compatible and, at doses at or below around 2 Gy, a DDREF value of about 2 is implied.

A.4.3. Relative biological effectiveness (RBE) and radiation weighting (w_R)

(A 101) The relationships between RBE and w_R were reviewed in *Publication 92* (ICRP 2003c). The outcome of this review, which involved input from ICRP Committees 1 and 2, was a recommendation that although the w_R values for protons and neutrons required revision, w_R values for other radiations given in *Publication 60* (ICRP 1991b) remained appropriate.

(A 102) For protons of energy >2 MeV it was judged in *Publication 92* that the w_R value of 5 given in *Publication 60* is a significant overestimate of their biological effectiveness and for incident protons of practical importance (> 10 MeV) a w_R of 2 was proposed. For neutrons, *Publication 92* proposed that ICRP continues the use of w_R values that depend upon the energy of the incident neutrons. However, the continuous function given in *Publication 92* (Fig. 1 on page 3) was recommended rather than the step function given in *Publication 60*. *Publication 92* noted that, for practical purposes, this procedure will reduce problems of computation of effective dose but should not be taken to imply precise knowledge of the underlying biological effectiveness. The issues of w_R for neutrons and photons/electrons have been considered further by ICRP Committee 2, and detailed judgements are given in Annex B of these Recommendations.

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(A 103) Those Auger-emitting radionuclides and compounds that have the potential to localise to the cell nucleus and bind to DNA were recognised in *Publication 60* as a special case for low-LET radiation. The Commission supports the view given in *Publication 92* that Auger emitters will continue to need special attention in radiological protection and that specific physiological and biophysical data would be needed in order to consider Auger-emitting compounds on a case-by-case basis.

A.4.4. Estimation of cancer risk from epidemiological data

(A 104) The Task Group that drafted this Annex was specifically charged by the Commission with developing nominal risk coefficients for cancer risk and providing recommendations on the transport of risk between populations, the estimation of radiation detriment and the derivation of tissue weighting factors. This was a major new element of work for ICRP Committee 1 and required input from Committee 2 and the Commission. The outcome of this work is summarised below.

Nominal risk coefficients, radiation detriment, and tissue weighting factors

(A 105) Nominal risk coefficients are derived by averaging sex and age-at-exposure lifetime risk estimates in representative populations. In general, cohort studies were preferred for risk assessment, because in retrospective case-control studies, selection biases may be a problem and the dose estimates can be highly uncertain when exposure data come from personal recall without documentation. The lifetime risk estimates are computed using risk estimates specific to various cancer sites. Radiation risk estimates are derived for incidence data for specific tumour sites when adequate dose response data are available from the Japanese Life Span Study (LSS), pooled analyses of multiple studies, or other sources. Incidence data tend to have less diagnostic misclassification than mortality data and provide better estimates for sites that have relatively low lethality. To simplify risk calculations by users of the ICRP system, estimates are derived for males and females combined. Because of the uncertainty in applying risk models generated from one population to another population with different cancer patterns, population-specific nominal risks are averages of risk estimates from alternative models; these are discussed in paragraphs A 110 – A 124. These nominal risks are computed for each site of interest and summed to give the population total nominal risk. The overall site-specific and total nominal risks are computed by averaging the population-specific average risks.

(A 106) Radiation detriment is a concept used to quantify the harmful effects of radiation exposure in different parts of the body. It is determined from nominal risk coefficients, taking into account the severity of the disease in terms of lethality and years of life lost. Total detriment is the sum of the detriment for each part of the body (tissues and/or organs).

(A 107) The concept of 'effective dose' associated with a given exposure involves weighting individual organs and tissues of interest by the relative detriments for these parts of the body. In such a system, the weighted sum of the tissue-specific dose equivalents, called the effective dose, should be proportional to the total estimated

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detriment from the exposure, whatever the distribution of equivalent dose within the body. The components of detriment are essentially the same for cancer and heritable disease and, if desired, these detriments may be combined.

(A 108) In general, the risk estimates summarised here are derived as averages across Asian and Euro-American populations. An attempt was made to choose an appropriate model to use for transferring risks across various populations whenever there is sufficient evidence to favour one model over another. The risk modelling was conducted principally with the data from the Japanese Life Span Study of A-bomb survivors (LSS), but the broader radiation epidemiology literature was examined for compatibility with the LSS-derived estimates. For several tissues it was possible to use a group of data sets to estimate cancer risk.

(A 109) The following text briefly outlines the general models of risk and the sources of data used, methodological aspects of the risk estimates, and the detriments associated with a range of tissues. Estimated numerical values and recommendations that derive from this work are summarised in Tables A.4.1, A.4.3, and A.4.4.

(A 110) ***Risk modelling.*** Within a given exposed population, comparable descriptions of the radiation-associated risk can be made using either excess relative risk (ERR) or excess absolute risk (EAR) models, so long as the models allow for variation in the excess risk with factors such as sex, attained age, and age-at-exposure. While suitably data-rich multiplicative (ERR) or additive (EAR) models lead to virtually identical descriptions of the excess risk in the population used to develop the risk estimates, they can lead to markedly different excess risk estimates when applied to populations with different baseline rates.

(A 111) Both ERR and EAR models were developed for oesophagus, stomach, colon, liver, lung, breast, ovary, bladder, thyroid and leukaemia (bone marrow). As noted below, *Publication 60* nominal risks were used for bone and skin cancers (ICRP, 1991b). Because the data for other human tissues and organs are insufficient to individually judge the magnitude of their radiation risk, they were consigned to a 'remainder' category (called 'other solid'). ERR and EAR models were also developed for this group.

(A 112) In general, the parameters in these risk models were estimated using incidence data from the studies of the Japanese atomic bomb survivors with follow-up from 1958 through to 1998 for solid cancers (Preston et al., 2007). For solid cancers these models involved a linear dose response allowing for modifying effects of sex, exposure age, and attained age. These effects were constrained to equal the values seen for all solid cancers as a group unless there were indications that these constraints resulted in a marked reduction in the goodness of fit when modelling cause-specific cancer types. Leukaemia risk estimates were based on an EAR model with a linear-quadratic dose response that allows for effect modification by sex, exposure age, and time following exposure (Preston et al., 1994). Model parameters are given in Section A.4.5.

(A 113) While the LSS studies do provide some information on skin cancer risks (Ron et al., 1998), it was judged that they may not be adequate for a general population because of differences in risk related to skin pigmentation. Therefore, the

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Table A.4.1. Summary of sex-averaged nominal risks and detriment.

Tissue	Nominal Risk Coefficient (cases per 10,000 persons per Sv)	Lethality fraction	Nominal risk adjusted for lethality and quality of life*	Relative cancer-free life lost	Detriment (relating to column 1)	Relative detriment+
a) Whole population						
Oesophagus	15	0.93	15.1	0.87	13.1	0.023
Stomach	79	0.83	77.0	0.88	67.7	0.118
Colon	65	0.48	49.4	0.97	47.9	0.083
Liver	30	0.95	30.2	0.88	26.6	0.046
Lung	114	0.89	112.9	0.80	90.3	0.157
Bone	7	0.45	5.1	1.00	5.1	0.009
Skin	1000	0.002	4.0	1.00	4.0	0.007
Breast	112	0.29	61.9	1.29	79.8	0.139
Ovary	11	0.57	8.8	1.12	9.9	0.017
Bladder	43	0.29	23.5	0.71	16.7	0.029
Thyroid	33	0.07	9.8	1.29	12.7	0.022
Bone Marrow	42	0.67	37.7	1.63	61.5	0.107
Other Solid	144	0.49	110.2	1.03	113.5	0.198
Gonads (Heritable)	20	0.80	19.3	1.32	25.4	0.044
Total	***1715***		***565***		***574***	***1.000***
b) Working age population (18–64 years)						
Oesophagus	16	0.93	16	0.91	14.2	0.034
Stomach	60	0.83	58	0.89	51.8	0.123
Colon	50	0.48	38	1.13	43.0	0.102
Liver	21	0.95	21	0.93	19.7	0.047
Lung	127	0.89	126	0.96	120.7	0.286
Bone	5	0.45	3	1.00	3.4	0.008
Skin	670	0.002	3	1.00	2.7	0.006
Breast	49	0.29	27	1.20	32.6	0.077
Ovary	7	0.57	6	1.16	6.6	0.016
Bladder	42	0.29	23	0.85	19.3	0.046
Thyroid	9	0.07	3	1.19	3.4	0.008
Bone Marrow	23	0.67	20	1.17	23.9	0.057
Other Solid	88	0.49	67	0.97	65.4	0.155
Gonads (Heritable)	12	0.80	12	1.32	15.3	0.036
Total	***1179***		***423***		***422***	***1.000***

* Defined as $R*q + R*(1 - q)* ((1 - q_{min}) q + q_{min})$, where R is the nominal risk coefficient, q is the lethality, and $(1 - q_{min}) q + q_{min}$ is the weight given to non-fatal cancers. Here q_{min} is the minimum weight for non-fatal cancers. The q_{min} correction was not applied to skin cancer (see text).

\+ The values given should not be taken to imply undue precision but are presented to 3 significant figures to facilitate the traceability of the calculations made.

Commission used the nominal skin cancer risk estimate of 0.1 per Gy from *Publication 59* (ICRP, 1991a). This estimate was also used in *Publication 60* (ICRP, 1991b). The nominal risk estimate for bone was also taken from *Publication 60* because the LSS atomic bomb studies provide no data, and other data sources were extremely limited. The low-LET estimate used in *Publication 60* was 0.00065 per Gy. It should

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Table A.4.2. Comparison of sex-averaged nominal risks and detriment in whole population based on different methods of calculation.

Tissue	Method of calculation	Nominal risk (cases per 10,000 persons per Sv)			Nominal risk adjusted for lethality and quality of life*	Detriment	Relative detriment+
		Total	Fatal	Non-fatal			
Oesophagus	Current Incidence	15.1	14.0	1.1	15.1	13.1	0.023
	Current Mortality	29.1	27.0	2.1	29.0	25.2	0.037
	BEIR VII	14.1	13.1	1.0	14.1	12.2	0.019
	Current ICRP 60	26.7	24.8	1.9	26.6	23.2	0.032
	ICRP 60 actual	31.6	30.0	1.6	31.5	24.3	0.033
Stomach	Current Incidence	79.1	65.5	13.5	77.0	67.7	0.118
	Current Mortality	72.0	59.7	12.3	70.1	61.7	0.091
	BEIR VII	96.3	79.8	16.5	93.8	82.5	0.129
	Current ICRP 60	56.2	46.6	9.6	54.7	48.1	0.067
	ICRP 60 actual	122.2	110.0	12.2	121.0	100.8	0.139
Colon	Current Incidence	65.4	31.3	34.2	49.4	47.9	0.083
	Current Mortality	71.8	34.3	37.5	54.2	52.6	0.078
	BEIR VII	74.5	35.6	38.9	56.2	54.5	0.085
	Current ICRP 60	245.3	117.2	128.1	185.1	179.5	0.249
	ICRP 60 actual	154.5	85.0	69.5	123.3	102.7	0.142
Liver	Current Incidence	30.3	28.9	1.4	30.2	26.6	0.046
	Current Mortality	67.5	64.4	3.1	67.4	59.3	0.088
	BEIR VII	40.0	38.2	1.8	39.9	35.1	0.055
	Current ICRP 60	15.8	15.0	0.8	15.7	13.8	0.019
	ICRP 60 actual	15.8	15.0	0.8	15.8	15.8	0.022
Lung	Current Incidence	114.2	101.5	12.6	112.9	90.3	0.157
	Current Mortality	110.8	98.6	12.2	109.6	87.7	0.130
	BEIR VII	136.9	121.8	15.1	135.4	108.3	0.169
	Current ICRP 60	70.3	62.5	7.8	69.5	55.6	0.077
	ICRP 60 actual	89.5	85.0	4.5	89.3	80.3	0.111
Bone	Current Incidence	7.0	3.2	3.9	5.1	5.1	0.009
	Current Mortality	7.0	3.2	3.9	5.1	5.1	0.008
	BEIR VII	7.0	3.2	3.9	5.1	5.1	0.008
	Current ICRP 60	7.0	3.2	3.9	5.1	5.1	0.007
	ICRP 60 actual	6.9	5.0	1.9	6.4	6.4	0.009
Skin	Current Incidence	1000.0	2.0	998.0	4.0	4.0	0.007
	Current Mortality	1000.0	2.0	998.0	4.0	4.0	0.006
	BEIR VII	1000.0	2.0	998.0	4.0	4.0	0.006
	Current ICRP 60	1000.0	2.0	998.0	4.0	4.0	0.006
	ICRP 60 actual	1000.0	2.0	998.0	4.0	4.0	0.006
Breast	Current Incidence	112.1	33.0	79.1	61.9	79.8	0.139
	Current Mortality	56.5	16.6	39.8	31.2	40.2	0.059
	BEIR VII	111.9	32.9	78.9	61.8	79.7	0.124
	Current ICRP 60	47.5	14.0	33.5	26.2	33.9	0.047
	ICRP 60 actual	40.0	20.0	20.0	30.0	36.3	0.050

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Table A.4.2. (*continued*)

Tissue	Method of calculation	Nominal risk (cases per 10,000 persons per Sv)			Nominal risk adjusted for lethality and quality of life*	Detriment	Relative detriment+
		Total	Fatal	Non-fatal			
Ovary	Current Incidence	10.6	6.0	4.6	8.8	9.9	0.017
	Current Mortality	21.2	12.0	9.2	17.6	19.7	0.029
	BEIR VII	11.5	6.5	5.0	9.6	10.7	0.017
	Current ICRP 60	23.4	13.3	10.2	19.4	21.8	0.030
	ICRP 60 actual	14.3	10.0	4.3	13.0	14.6	0.020
Bladder	Current Incidence	43.4	12	31	23.5	16.7	0.029
	Current Mortality	71.7	20	51	38.7	27.5	0.041
	BEIR VII	51.9	15	37	28.0	19.9	0.031
	Current ICRP 60	100.4	29	72	54.2	38.5	0.053
	ICRP 60 actual	60.0	30	30	45.0	29.3	0.040
Thyroid	Current Incidence	32.5	2.2	30.3	9.8	12.7	0.022
	Current Mortality	23.3	1.6	21.8	7.1	9.1	0.013
	BEIR VII	32.0	2.1	29.9	9.7	12.5	0.020
	Current ICRP 60	120.3	8.0	112.3	36.4	47.0	0.065
	ICRP 60 actual	80.0	8.0	72.0	15.2	15.2	0.021
Bone Marrow	Current Incidence	41.9	28.0	13.9	37.7	61.5	0.107
	Current Mortality	54.2	36.3	18.0	48.9	79.6	0.118
	BEIR VII	41.9	28.0	13.9	37.7	61.5	0.096
	Current ICRP 60	46.9	31.4	15.6	42.3	68.9	0.096
	ICRP 60 actual	50.5	50.0	0.5	50.5	104.0	0.143
Other Solid	Current Incidence	143.8	70.5	73.3	110.2	113.5	0.198
	Current Mortality	226.3	111.0	115.3	173.4	178.6	0.264
	BEIR VII	163.3	80.1	83.2	125.1	128.9	0.201
	Current ICRP 60	196.4	96.3	100.0	150.5	155.0	0.215
	ICRP 60 actual	70.4	50.0	20.4	64.5	58.7	0.081
Gonads (Heritable)	Current Incidence	20.0	16	4	19.3	25.4	0.044
	Current Mortality	20.0	16	4	19.3	25.4	0.038
	BEIR VII	20.0	16	4	19.3	25.4	0.040
	Current ICRP 60	20.0	16	4	19.3	25.4	0.035
	ICRP 60 actual	100.0	100	0	100.0	133.0	0.183
Total	Current Incidence	1715.4	414	1301	564.8	574.3	1
	Current Mortality	1831.4	503	1328	675.4	675.8	1
	BEIR VII	1801.2	474	1327	639.6	640.4	1
	Current ICRP 60	1976.3	479	1497	709.2	719.9	1
	ICRP 60 actual	1835.8	600	1236	709.3	725.3	1

Footnote and numerical values as per Table A.4.1.

Additional notes: The BEIR VII estimates are based on application of the BEIR VII risk models to the combined Euro-American and Asian populations with an assumed DDREF of 2. Nominal risks and detriment values would be increased by 4/3 if the BEIR VII DDREF of 1.5 were used. BEIR VII risks for skin, bone surface, and gonads are taken as the same as the ICRP values since risk estimates for these outcomes were not considered in the BEIR VII lifetime risk estimates. The 'Current ICRP 60' estimates are based on application of the *Publication 60* risk models to the Euro-American and Asian populations used here with an assumed DDREF of 2. The 'ICRP 60 actual' estimates were determined from the data in *Publication 60*.

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Table A.4.3. Proposed tissue weighting factors.

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder Tissues* (Nominal w_T applied to the average dose to 14 tissues)	**0.12**	0.72
Gonads	**0.08**	0.08
Bladder, Oesophagus, Liver, Thyroid	**0.04**	0.16
Bone surface, Brain, Salivary glands, Skin	**0.01**	0.04

* Remainder Tissues (14 in total): Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate, Small intestine, Spleen, Thymus, Uterus/cervix.

Table A.4.4. Detriment adjusted nominal risk coefficients for cancer and heritable effects (10^{-2} Sv^{-1})[1].

Exposed population	Cancer		Heritable effects		Total	
	Present	ICRP 60	Present	ICRP 60	Present	ICRP 60
Whole	5.5	6.0	0.2	1.3	5.7	7.3
Adult	4.1	4.8	0.1	0.8	4.2	5.6

[1] Values from Tables A.4.1a, A.4.1b, and *Publication 60*.

be noted that the ICRP risk estimate for bone cancer was based on average bone dose from radium–244 while current dosimetric models estimate doses to bone surfaces. As discussed by Puskin et al. (1992), the risk estimate would be a factor of 9 lower if calculated on the basis of dose to the bone surface. However, proposed changes in bone dosimetry will reduce this difference. For the purposes of the present report, the risk estimate based on average bone dose is used while recognising its possible conservatism.

(A 114) The risk models described above were used to compute sex-specific lifetime risk estimates for a range of ages at exposure (0 to 85 years in 5-year intervals) in Asian and Euro-American composite populations as described subsequently. Lifetime risks for exposure ages were then averaged using weights reflecting the age distribution of the full population or for a working age (18–64 year old) population.

(A 115) In *Publication 60*, nominal cancer risks were computed based on mortality data but, in the current report, risk estimates are based principally on incidence data. The reason for the change is that incidence data provide a more complete description of the cancer burden than do mortality data, particularly for cancers that have a high survival rate. In addition, cancer registry (incidence) diagnoses are more accurate and the time of diagnosis is more precise. It is recognised, however, that incomplete coverage of the A-bomb population because of migration from Hiroshima or Nagasaki introduces a factor of uncertainty on risk estimates based on these cancer incidence data. At the time of *Publication 60*, comprehensive incidence data were not available. Since then, a thorough evaluation of cancer incidence in the Life Span Study (LSS) of Japanese atomic bomb survivors has been published (Thompson et al., 1994; Preston et al., 1994). Site-specific risk estimates were taken from the most recent solid cancer incidence analyses of the atomic bomb survivor LSS (Preston

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et al., 2007), with follow-up from 1958 through 1998, and adjusted to reduce the bias in risk estimates that is due to uncertainty in individual dose estimates (Pierce et al., 1990). The newly implemented atomic bomb dosimetry system, DS02, is a considerable improvement over DS86. On average, the DS02 dose estimates are slightly greater than the DS86 estimates. Risk estimates using the two systems differ by less than 10% (Preston et al., 2004).

(A 116) Although the primary estimates are based on models derived from the LSS data, information from other radiation-exposed populations was also considered. Such information is available from studies of:

- Patients with therapeutic or diagnostic exposures to radiation;
- Workers exposed to radiation in the course of their job, e.g., uranium miners;
- Persons with environmental exposures, e.g., from fallout or from natural radiation.

(A 117) These studies have been reviewed in detail by UNSCEAR (2000) and the International Agency for Research on Cancer (IARC 2000, 2001). Some of these studies are more informative than others about radiation risks. The LSS is particularly valuable in estimating radiation risks for a general population, because of the very long, mainly prospective follow-up, the large size of the cohort, and the inclusion of persons of all ages and both sexes who received a wide range of doses. In contrast, many studies of medical exposures lack the sample size and dosimetry quality for precise estimation of risk as a function of dose (NAS/NRC 2006). Also, studies of therapeutic exposures often involve doses in excess of 5 Gy, where cell killing may lead to an under-estimation of the cancer risk per unit dose.

(A 118) However, studies other than the LSS can provide information on the effects of exposure received under different circumstances, such as exposure to high-LET rather than low-LET radiation, exposures received in a chronic or fractionated manner rather than acutely, or risks in countries other than Japan. For example, because the baseline rates of breast cancer are very low in Japan, data from seven cohorts in North America and Western Europe were used in addition to the LSS for determining the site-specific risk estimate (Preston et al. 2002). Also, for thyroid cancer, data from four populations exposed to radiation for medical reasons in various countries were considered in addition to the LSS (Ron et al. 1995). As mentioned earlier, the nominal risk estimates for bone and skin are those used in *Publication 60* (ICRP 1991b). These estimates are largely based on studies of groups with medical exposures (e.g., intakes of radium–224 in the case of bone).

(A 119) For cancers at some sites there is reasonable compatibility between the data from the LSS and those from other sources. However, it is recognised by the Commission that there are indications of differences in radiation risks for a number of sites, e.g., lung when compared with radon-exposed miners (UNSCEAR 2000), although here the differences – within a factor of 2–3 – are not large relative to the uncertainties in these estimates. More direct information on the effects of low level radon exposures comes from recent combined analyses of case-control studies that show raised risks of lung cancer from radon exposure in homes (Darby et al.

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2005, Krewski et al. 2005, Lubin et al. 2004). Precise comparison with estimates based on the LSS and the miner studies is difficult but, bearing in mind the various uncertainties, the findings appear to be broadly compatible. In *Publication 60*, the liver cancer risk estimate was derived from studies of patients injected with the radioactive contrast medium Thorotrast, whilst in the current report the LSS liver cancer risk estimate was preferred. The LSS estimate is higher than that of other groups exposed to x or gamma radiation (UNSCEAR 2000), probably because of a reported strong interaction between hepatitis virus and radiation in the LSS (Sharp et al. 2003). However, as indicated below, the estimate derived here based on the LSS is similar to that in *Publication 60*. More generally, when the LSS cancer incidence risks were compared to those from medically or occupationally irradiated populations exposed to low-LET external radiation, the risk estimates were broadly compatible (NAS/NRC 2006).

(A 120) *Cancer risk in different tissues.* Nominal cancer risks and tissue weights were developed for 12 tissues and organs (oesophagus, stomach, colon, liver, lung, bone, skin, breast, ovary, bladder, thyroid, and red bone marrow) with the remaining tissues and organs grouped into one 'remainder' category. These individual tissues and organs were selected because it was deemed that there was sufficient epidemiological information on the tumorigenic effects of radiation to make the judgements that were necessary for estimating cancer risks. Leukaemia, excluding chronic lymphocytic leukaemia (CLL), and multiple myeloma were included in the bone marrow category. The remainder category also includes other tissues not explicitly evaluated as individual cancer sites.

(A 121) *Composite populations.* Composite baseline rates were computed using incidence rates averaged across six populations for cancers of the oesophagus, stomach, colon, liver, lung, female breast, ovary, bladder, thyroid, leukaemia (excluding CLL) and solid cancers combined. The aim was to compile rates for representative populations in different parts of the world. Population-based cancer incidence rates were obtained from the 8th edition of Cancer Incidence In Five Continents (Parkin et al. 2002) and population size data were obtained from the WHO international mortality statistics database. In Annex B of *Publication 60* (ICRP 1991b), risks were calculated separately for five different populations. The approach taken here is slightly different, in that cancer rates were compiled for selected Asian (Shanghai, Osaka, Hiroshima and Nagasaki) and Euro-American (Sweden, United Kingdom, US SEER) populations with long-running cancer registries. These rates are shown in Section A.4.5. An unweighted average of the Asian and the Euro-American data was calculated to form a composite population.

(A 122) Sex-specific, all-stage relative survival statistics from the US SEER programme for 1994–1999 (5-year survival) and 1979–1999 (20-year survival) were averaged to compute overall relative survival rates for different cancer sites. Although the SEER relative survival rates are higher than those found for many other European and Asian countries, reducing the survival rates did not change estimates of relative detriment appreciably.

(A 123) *Heritable risks.* The estimate of genetic (heritable) risk from radiation has been substantially revised since the *Publication 60* report as a result of both new

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information that has become available and the work of ICRP during the interim. These revised estimates and their derivation are given in Section A.6. Several factors have led to this revision of genetic risk estimates; in brief:

- Most radiation-induced mutations are large multigene deletions, which are more likely to cause multisystem developmental abnormalities rather than single-gene (i.e., Mendelian) diseases. Importantly, only a fraction of these are likely to be compatible with live births.
- Nearly all chronic diseases have a genetic component, but because most of these are multigenic and multifactorial, the mutation component (i.e., the responsiveness of these diseases to an alteration in mutation rate) is small, so that chronic diseases respond only minimally to a radiation-induced increase in mutation rate.
- *Publication 60* (ICRP 1991b) made the implicit assumption that all genetic diseases should be treated as lethal. In view of the range of severity and lethality for the various types of genetic disease, the lethality fraction for genetic diseases has now been explicitly designated as 80%.
- New genetic risk coefficients recommended by ICRP consider exposure and genetic risk for two generations only; the equilibrium value used in *Publication 60* is judged to be of limited scientific validity because of the unsupported assumptions necessary on selection coefficients, mutation component and population changes over hundreds of years.

(A 124) As a result, the risk of heritable effects in the whole population associated with gonadal dose is now estimated to be around 20 cases per 10,000 people per Sv, rather than around 100 cases per 10,000 per Sv in *Publication 60* (see Section 6, Table 6.6). As in *Publication 60*, the risk of heritable effects in the working population is taken to be 60% of that for the whole population. The corresponding relative contribution of the gonadal dose to the total detriment is now estimated as 3–4%, versus the former ~18%.

(A 125) ***Methodological aspects.*** *Uncertainty and sensitivity analyses.* There are uncertainties in radiation risk estimates which stem from several sources. The most familiar is statistical uncertainty, represented by confidence limits or statistical likelihood distributions. For a chronic or low-dose exposure, the estimate and its statistical uncertainty are divided by an uncertain dose and dose-rate effectiveness factor (DDREF), a process that both reduces the estimate and further increases its uncertainty (see below).

(A 126) When an estimate based on a particular exposed population is applied to other populations or to other radiation sources, further uncertainty is introduced. Differences between radiation sources can produce uncertainty owing to random or systematic error in dose estimates in either the original or the secondary population.

(A 127) Risk-based radiological protection depends heavily on the assumption that estimates based on studies of informative exposed populations, such as the Life Span Study cohort of atomic bomb survivors, can be applied to other exposed populations. Combined analyses of dose-response data from different populations (e.g., Preston et al. 2002) provide valuable information relevant to that assumption.

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Unfortunately, such information is available for very few site-specific cancers. Transfers of risk estimates between populations pose a particularly difficult problem for cancer sites for which baseline rates differ widely between the two populations. This problem is discussed in more detail below.

(A 128) Other major sources of uncertainty include possible interaction of radiation exposure with other cancer risk factors, notably including smoking history in the case of lung cancer, and reproductive history in the case of female breast cancer. This problem is similar to that of transfer of risk estimates between populations, in that the interaction can be represented as an uncertain linear combination of an additive and a multiplicative model. However, there is epidemiological evidence favouring an additive or submultiplicative interaction in the case of lung cancer and smoking (Pierce et al. 2003, Travis et al. 2002, Lubin et al. 1995), and a multiplicative interaction in the case of breast cancer and reproductive history (Land et al. 1994).

(A 129) Another source of uncertainty is the relative biological effectiveness, relative to high-energy photons, of radiations of different qualities including medical x rays in the 30–200 keV range, electrons, neutrons, protons, and alpha particles. Quantification of such uncertainties has been discussed in detail elsewhere, e.g., NCI/CDC (2003). The use of central values is preferred by the Commission for radiological protection purposes, but it should be kept in mind that RBE values for specific radiations are intrinsically uncertain. Other aspects of uncertainty associated with the possible existence of a low-dose threshold for cancer risk are summarised in Section A.4.4, paragraphs A 173 – A 187. Uncertainties associated with dose estimates for internal radionuclides (e.g., CERRIE, 2004) are noted in *Publication 99* (ICRP, 2005d).

(A 130) *Dose and dose-rate effectiveness factor.* Because it is difficult to detect small risks in epidemiological studies, the dose-specific estimates of radiation-related risk in this report are largely determined by people exposed to acute doses of 200 mSv or greater. However, many of the more contentious issues in radiation protection involve risks from continuous exposures, or fractionated exposures with acute fractions of a few mSv or less. Experimental investigations tend to show that fractionation or protraction of dose is associated with reduced risk, suggesting that dose-specific estimates based on high-dose, acute exposure data should be divided by a dose and dose-rate effectiveness factor (DDREF) for applications to low-dose, continuous, or fractionated exposures.

(A 131) As already noted, direct estimation from epidemiological studies of cancer risks from doses below a few hundred mSv is difficult, largely for reasons of statistical power. Combined analyses of datasets can help increase statistical power, although precise estimation of risks is currently not possible. A recent example concerns a combined analysis of data on cancer mortality among nuclear workers in 15 countries (Cardis et al. 2005). Notwithstanding the large population (around 400,000 workers in the main analysis), the cohort is still relatively young and only 6% of the workers had died by the end of follow-up. Consequently, the confidence intervals for the estimated trends in cancer risk with dose were wide. In particular, the findings were consistent with risks extrapolated from high-dose, acute exposure data using

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a DDREF of 2, as well as with a range of other values. Furthermore, part of the increased risk observed for cancers other than leukaemia appeared to be due to confounding caused by smoking. This highlights the impact that relatively small biases might have on studies at low doses.

(A 132) The magnitude of DDREF is uncertain, and has been treated as such in a number of recent reports based on quantitative uncertainty analysis; for example, NCRP (1997), EPA (1999), and NCI/CDC (2003). However, the mean of the probabilistic uncertainty distribution for DDREF employed in those analyses differs little from the value of 2 recommended in *Publication 60* (ICRP, 1991b) and UNSCEAR (1993). A DDREF of 2 is also generally compatible with the animal data noted in Section A.4.2. Recognising uncertainties, the Commission recommends that a DDREF of 2 continues to be used for radiological protection purposes.

(A 133) The Commission notes that the BEIR VII Committee (NAS/NRC, 2006) employed a Bayesian statistical approach to the choice of DDREF based upon a combination of human data from the LSS and results from appropriately selected animal studies. This analysis indicated that DDREF values in the range 1.1–2.3 were consistent with these data, and BEIR VII chose a DDREF value of 1.5 for the purposes of cancer risk estimation. BEIR VII discusses the elements of subjectivity that are inherent in choices of DDREF, and the Commission stresses that its recommendation to retain an ICRP DDREF summary value of 2 for radiological protection purposes is a broad judgement which embodies elements of both subjectivity and probabilistic uncertainty.

(A 134) *Sex averaging.* Some radiation-related cancers are sex-specific and, for many others, sex is a major modifier of radiation-related risk. In accordance with current ICRP procedures, intermediate and final numerical risk estimates presented here are sex-averaged. Radiation risks were also calculated by retaining sex specificity of intermediate results and sex-averaging only at the final stage. The final results were similar, within acceptable limits, for the two methods of calculation, and sex-specific data are not recommended for the general purposes of radiological protection.

(A 135) *Transfer of risk between populations.* If two populations differ with respect to prevalence of known modifiers of radiation-related risk, their responses to radiation exposure might be expected to differ. However, even in the absence of such information, it is problematic to transfer site-specific estimates of radiation-related risk from one population to the other if the corresponding baseline rates differ. For (an extreme) example, the LSS population provides by far the most usable estimates available of radiation-related gastric cancer risk, but age-specific baseline rates differ by a factor of 12 between Japan and the United States. There is rough equivalence between dose-specific excess absolute risk (EAR_{LSS}) and the product of excess relative risk (ERR_{LSS}) and baseline rates for the population of Japan, but the relationship

$$EAR_{LSS} = ERR_{LSS} \times baseline_{Japan}$$

corresponds approximately to

$$EAR_{LSS} = 12 \times ERR_{LSS} \times baseline_{US}$$

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(A 136) Thus, a multiplicative model estimate of excess risk for stomach cancer in the US population based on an ERR model, i.e.,

$$\mathrm{ERR_{mult}} = \mathrm{ERR_{LSS}}$$

is about one twelfth as high as the estimate based on directly transferring the $\mathrm{EAR_{LSS}}$:

$$\mathrm{ERR_{add}} = \mathrm{EAR_{LSS}}/\mathrm{baseline_{US}} = \mathrm{ERR_{LSS}} \times (\mathrm{baseline_{Japan}}/\mathrm{baseline_{US}})$$

(A 137) Assuming that ionising radiation exposure acts primarily as a cancer initiator, multiplicative transfer would be plausible if the difference in population rates were associated with differential exposure to cancer promoters, and additive transfer would be plausible if the rate difference could be ascribed to differential exposure to competing cancer initiators. Given little information about radiation-related stomach cancer risk in the US population, or about modification of radiation-related risk by whatever factors are responsible for the 12-fold difference between gastric cancer rates in the two countries, it would not be unreasonable to consider all estimates of the form

$$\mathrm{ERR_{US}}(p) = p \times \mathrm{ERR_{add}} + (1 - p) \times \mathrm{ERR_{mult}}$$

for $0 \leqslant p \leqslant 1$, as being equally likely. With this approach, the overall uncertainty is high, and the mean value, $\mathrm{ERR_{US}}(1/2)$, does not really represent the range of (presumably) equally likely transfer estimates.

(A 138) For most sites, the difference between Japanese and US rates is considerably less than 12-fold, which means that inability to discriminate between the additive and multiplicative transfer models is less consequential. However, among the sites considered for the present report, only for lung, breast, and thyroid was it considered that there was sufficient information to justify a representative value other than $\mathrm{ERR_{US}}(1/2)$.

(A 139) Because a pooled analysis of radiation effects on breast cancer risk (Preston et al., 2002) provides strong evidence against the use of common ERR models, breast cancer risks were based solely on an EAR model, namely that based on the A-bomb data. However, the use of EAR models for predicting thyroid cancer risks is problematic because variation in screening intensity will have a marked effect on the rate of radiation-associated thyroid cancers. Therefore, thyroid cancer risks were based solely on the ERR model developed from the pooled analysis of radiation-associated thyroid cancer risks (Ron et al., 1995).

(A 140) Therefore, the population risks were defined as weighted averages of the additive (absolute) and multiplicative excess risk estimates with weights based on judgements concerning the relative applicability of the two risk estimates. Weights of 0.5 were used for all tissues except breast and bone marrow for which only an EAR model was used, thyroid and skin for which only an ERR model was used, and lung for which the ERR model was given a weight of 0.3 because of suggestions in the atomic bomb survivor data that the EAR is more comparable across sexes than the ERR, and also that radiation dose and smoking history interact additively as lung cancer risk factors (Pierce et al., 2003).

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(A 141) *Computation of radiation detriment.* As in *Publication 60*, the detriment for a tissue, T, is defined as

$$D_T = (R_{F,T} + q_T R_{NF,T}) l_T$$

where R_F is the nominal risk of fatal disease, R_{NF} is the nominal risk of non-fatal disease, q is a non-fatal weight (between 0 and 1) reflecting the reduced quality of life associated with living with a serious illness, and l is the average life lost due to the disease relative to normal life expectancy, expressed relative to the average over all cancers. As discussed below, the quality of life factor is a function of the lethality (k) of the disease and a subjective judgement accounting for pain, suffering, and adverse effects of treatment. Box 1 summarises the steps by which radiation detriment was calculated for the purposes of developing a system of tissue weighting.

(A 142) Since incidence data are being used here, the nominal risk coefficients are $R_I = R_F + R_{NF}$ and the detriment is computed as

$$(k_T R_{I,T} + q_T(1 - k_T) R_{I,T}) l_T = R_{I,T}(k_T + q_T(1 - k_T)) l_T$$

(A 143) The computations in *Publication 60* were based on nominal mortality risk coefficients, R_F, and q was taken to be equal to the lethality fraction k. Thus, the ICRP *Publication 60* cause-specific detriment is $(R_F + k\,(1 - k)R_F\,/k)l$ which is equal to $R_F\,(2\text{-}k)l$ (cf pages 134–136 and Table B20 in *Publication 60*), where

$$R_{NF} = (1 - k)R_F/k.$$

(A 144) *Quality of life detriment.* Cancer survivors generally experience adverse effects on their quality of life. Thus, the Commission judges that cancers should be weighted not only by lethality but also for pain, suffering, and any adverse effects of cancer treatment. To achieve this, a factor termed q_{min} is applied to the non-lethal fractions of cancers to produce an adjusted lethality fraction termed q_T. The formula used to calculate q_T with an adjustment for non-lethal detriment is:

$$q_T = q_{min} + k_T(1 - q_{min})$$

where k_T is the lethality fraction and q_{min} is the minimum weight for non-lethal cancers.

(A 145) The value of q_{min} was set equal to 0.1 (in most instances the result is not highly sensitive to the value chosen). In effect, the q_{min} adjustment has an impact upon detriment calculations in proportion to the fraction of cancers that are non-lethal. Accordingly, highly lethal cancers such as lung and stomach cancer are little affected by q_{min} whereas relatively non-lethal cancers such as breast or thyroid are. For example, if the lethality of a cancer type was 0.30, the adjusted q_T would be 0.37. However, the q_{min} adjustment was not used for skin cancer because radiogenic skin cancer is almost exclusively of the basal cell type which is usually associated with very little pain, suffering or treatment sequelae.

(A 146) *Lethality adjustment of nominal risk.* The nominal risk coefficients are adjusted to reflect the relative lethality for the cancers (or heritable effects) that occur. Highly lethal cancers receive a relatively greater weight than those that seldom cause death. The lethality adjustment is given by $(R \times q)$, where R is the nominal risk

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coefficient for a tumour site and q is its lethality fraction, derived from national cancer survival data.

(A 147) *Relative life lost.* Relative years of life lost is an important component of the detriment computation. Average years of life lost for a given cause was computed for each sex in each composite population as the average over ages at exposure and subsequent attained ages of the residual lifetime. The weights were equal to the number of deaths from the cause of interest in each age group. These were converted to relative values by division by the average years of life lost for all cancers.

(A 148) Table A.4.5 in Section A.4.5 presents the lethality factors, non-fatal case weights, and relative life lost values used in the current computations. *Publication 60* values are shown for comparison.

(A 149) ***Principal features of new estimates of cancer risk.*** In *Publication 60* the ERR and EAR models were given equal weights for various tissues, except for bone marrow. In the present assessment, the relative weights assigned to the ERR and EAR models were allowed to depart from 50:50 when warranted by the available data. This made a more realistic model for the inter-country transfer of radiogenic breast cancer risks, and largely prevented the potential problem of thyroid cancer or skin cancer risk estimates being affected by differing degrees of cancer screening.

(A 150) The present relative detriments (Table A.4.1) are similar to the values calculated in *Publication 60* except for four tissue groups: breast, bone marrow, remainder tissues and gonads. There appear to be several reasons why the relative detriment for breast cancer has increased from 0.05 to 0.139. Those exposed as juveniles in the LSS cohort now make a larger contribution to the overall breast cancer risk, whereas the mortality data used for the *Publication 60* analysis only partially reflected this contribution. Furthermore, in the current incidence analyses (Preston et al. 2007), the ERR estimates for women exposed over age 40 years are higher than those used in *Publication 60*. In the 1958–1987 LSS Tumour Registry report on radiation and solid cancer incidence (Thompson et al. 1994), breast cancers contributed about 11% of the total excess solid cancers as averaged over males and females. In the current analyses, breast cancers account for about 18% of the radiation-associated solid cancers. Studies of other exposed populations have confirmed the substantial breast cancer risk from radiation (Preston et al. 2002). On the other hand, the lethality fraction for breast cancer has decreased in the past 15 years, probably reflecting increased early detection and improved treatments, but this appears to have little impact on the relative detriment estimates.

(A 151) Improved description of the temporal diminution of leukaemia risk has contributed to a reduction in the relative detriment for bone marrow from 0.143 to 0.101. The reduction of gonadal risk has already been explained above and pertains to new information and a revised approach for assessing risks of heritable disease.

(A 152) The further accumulation of LSS data in the period following *Publication 60* has significantly influenced the 'remainder tissues' category. There is now evidence for excess radiation risk, in the aggregate, among a variety of other tissues, although the degree of risk for any single tissue is unclear. Since the risk in the remainder

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category is spread over a large number of tissues and organs, the judgement of the Commission is that any given tissue should receive a small weight. This judgement

Box A.1. Steps in the development of the tissue weighting system.

The development of the tissue weighting system was based upon relative radiation detriment, primarily for cancer. The sequential steps used were as follows:

a) Determine lifetime cancer incidence risk estimates for radiation-associated cancers: For 14 organs or tissues, male and female lifetime excess cancer risks were estimated using both the excess relative risk (ERR) and excess absolute risk (EAR) models and were then averaged across sexes.
b) Apply a dose and dose-rate effectiveness factor (DDREF): The lifetime risk estimates were adjusted downward by a factor of two to account for a DDREF (except for leukaemia, where the linear-quadratic model for risk already accounts for the DDREF).
c) Transfer risk estimates across populations: To estimate radiation risk for each cancer site, a weighting of the ERR and EAR lifetime risk estimates was established that provided a reasonable basis for generalising across populations with different baseline risks. (ERR:EAR weights of 0:100% were assigned for breast and bone marrow, 100:0% for thyroid and skin, 30:70% for lung, and 50:50% for all others).
d) Nominal risk coefficients: These weighted risk estimates, when applied to and averaged across seven western and Asian populations, provided the nominal risk coefficients given in Tables A.4.1 and A.4.2.
e) Adjustment for lethality: The lifetime risks for respective cancer sites, which were based on excess incident cancers, were converted to fatal cancer risks by multiplying by their lethality fractions, as derived from representative national cancer survival data.
f) Adjustment for quality of life: A further adjustment was applied to account for the morbidity and suffering associated with non-fatal cancers.
g) Adjustment for years of life lost: Since the age distributions of types of cancers differ, the average ages of the several types of cancer were estimated from national cancer data and converted to average years of life lost when a cancer occurs. An adjustment for years of life lost was then applied to the result of the previous steps.
h) Radiation detriment: The results of the calculations above yielded an estimate of the radiation detriment associated with each type of cancer. These, when normalised to sum to unity, constitute the relative radiation detriments in Table A.4.1.
i) Tissue weighting factors: Since the detailed relative radiation detriments in Table A.4.1 are imprecise because of uncertainties associated with their estimation, they were grouped into four categories broadly reflecting the relative detriments. A group of residual 'remainder tissues' was also added to account for radiation risks to organs or tissues for which detailed radiation-risk calculations were uninformative.

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is consistent with the LSS and/or other evidence suggesting the risk is probably very small or that evidence is lacking.

(A 153) In order to provide additional supporting information on factors that influence detriment estimates, the Commission computed site-specific, lethality adjusted nominal risks and detriment values using various methods. The methods used were: 1) the current incidence-based estimates; 2) mortality-based computations using risk models based on the most recent LSS mortality data (Preston et al. 2003) applied to the current composite populations together with the current lethality and life lost factors (i.e., the same as (1), but using risk models derived from current mortality rather than incidence data); 3) mortality-based computations using *Publication 60* ERR models (Table 1, Land and Sinclair 1991) applied to the current composite populations together with the current lethality and life lost factors (i.e., the same as (1), but using the *Publication 60* relative risk models for mortality in place of the models based on current incidence data); and 4) the actual *Publication 60* values.

(A 154) Results of these computations are shown in Table A.4.2. Table A.4.2 also includes computations of relative detriment based upon application of the BEIR VII models (NAS/NRC, 2006) to the combined Euro-American and Asian populations with an assumed DDREF of 2 (see Table A.4.2 footnote). Parameter estimates for the risk models used in method 2 are given in Section A.4.5. It can be seen that the values of relative detriment using incidence- and mortality-based risk models (i.e., approaches (1) and (2) above) are generally similar. There are, however, greater differences for some tissues in respect of the application of *Publication 60* methodology to current data ('Current ICRP 60') and the specific published *Publication 60* values ('ICRP 60 actual'). The application of BEIR VII models (NAS/NRC, 2006) shows similar degrees of difference in relative detriment for some tissues. However, in only a few instances were these differences greater than a factor of 3, and total detriment differed by a factor of less than 2.

(A 155) Overall, these comparative calculations suggest that LSS-based central estimates of radiation cancer risk are reasonably robust and not highly sensitive to choices of risk models.

(A 156) During the computation of sex-averaged values for detriment based on cancer incidence and mortality data the Commission was required to compute male- and female-specific data. These data (Tables A.4.18 and A.4.19 of Section A.4.6) do not contribute specifically to the formulation of the ICRP tissue weighting scheme as summarised in Box A.1, but can act to inform other related judgements. It is emphasised that these sex-specific data have limited utility because the Commission's estimates of nominal risk relate to a nominal population of females and males with typical age distributions and are computed by averaging over age groups and sex; the dosimetric quantity, effective dose, is also computed by age- and sex-averaging.

(A 157) ***The use of relative detriment from incidence data for a tissue weighting system.*** The Commission has made a policy decision that there should be a single set of w_T values that are averaged over both sexes and all ages.

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(A 158) However, whilst adhering to this policy, the Commission fully recognises that there are significant differences in risk between males and females (particularly for the breast) and in respect of age at exposure.

(A 159) A set of w_T values could be proposed that closely follows the respective values of relative detriment based on incidence data given in Table A.4.1 together with the supporting comparative data of Table A.4.2. However, the Commission feels that additional judgements need to be exercised to include subjective factors, not reflected in the mathematical formulation of detriment. In particular, the following judgements were applied:

- The detriments for heritable effects and cancer following gonadal irradiation were aggregated to give a w_T of 0.08.
- The detriment of thyroid cancer was set at 0.04 to take account of the concentration of cancer risk in childhood, i.e., young children are considered to be a particularly sensitive subgroup.
- Cancer risk in salivary glands and brain, whilst not specifically quantifiable, is judged to be greater than that of other tissues in the remainder fraction and, for this reason, each is ascribed a w_T of 0.01.

(A 160) Re-ordering of w_T values using the above judgements was made ensuring that these values did not diverge from the relative detriments of Table A.4.1 by more than around two-fold. This reassignment gives a w_T value for the remainder tissues of 0.12. The Commission presents a new proposal on the way in which the weighting of remainder tissues is treated.

(A 161) According to this proposal the w_T for remainder tissues (0.12) is divided equally between the 14 tissues given in the footnote to Table A.4.3, 0.0086 each, which is lower than the w_T for the lowest of the named tissues (0.01). The low cancer risk in connective tissues is taken into account through its contribution to cancer in the named organs specified in Table A.4.3. Cancer risk in adipose tissue is judged to be insignificant and, for this reason, it has not been included in remainder tissues. The number of tissues included in remainder could be increased if necessary. The system preserves additivity in effective doses. This is judged to be an appropriate simplification of the scheme of *Publication 60* in which the w_T for the remainder is divided among the five remainder tissues which receive the highest dose, i.e., a non-additive system. Mass weighting of tissues in the remainder fraction was explored but rejected. The principal reason for this rejection was that the very large disparities in tissue masses caused unacceptable distortions of effective dose for certain radionuclides.

(A 162) On the basis of the detriment data of Tables A.4.1 and A.4.2, plus the judgements summarised above, the Commission proposes the tissue weighting scheme given in Table A.4.3. This scheme which seeks to generally represent tissue-specific radiation detriment is, of necessity, imprecise. In particular, for the remainder tissues there is little or no epidemiological evidence of radiation-associated cancer for individual tissues, and their inclusion is largely a prudent measure. The Commission also emphasises that w_T is solely a radiation protection quantity and is not intended for other purposes, e.g., in judging radiation causation of cancers.

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Nominal risk coefficients for cancer and heritable effects

(A 163) New data on the risks of radiation-induced cancer and heritable effects have been used by the Commission in risk modelling and disease detriment calculations in order to estimate nominal risk coefficients.

(A 164) On the basis of these calculations (Table A.4.1) the Commission proposes nominal risk coefficients for lethality-adjusted cancer risk as 5.5 10^{-2} Sv^{-1} for the whole population and 4.1 10^{-2} Sv^{-1} for adult workers aged 18–64. For heritable effects, the lethality-adjusted nominal risk in the whole population is estimated as 0.2 10^{-2} Sv^{-1} and in adult workers as 0.1 10^{-2} Sv^{-1}. These estimates are shown in Table A.4.4, where they are compared with the estimates of detriment used in the 1990 Recommendations of ICRP *Publication 60*. These estimates are intended to apply only to populations and are not recommended for use in estimating risks in individuals or subgroups.

(A 165) In respect of Table A.4.4 it is important to note that the detriment-adjusted nominal risk coefficient for cancer estimated here has been computed in a different manner from that of *Publication 60*. The present estimate is based upon lethality/life-impairment-weighted data on cancer incidence with adjustment for relative life lost, whereas in *Publication 60* detriment was based upon fatal cancer risk weighted for non-fatal cancer, relative life lost for fatal cancers and life impairment for non-fatal cancer. In this respect it is also notable that the detriment-unadjusted nominal risk coefficient for fatal cancer in the whole population that may be projected from the cancer incidence-based data of Table A.4.1a is around 4% per Sv as compared with the *Publication 60* value of 5% per Sv. The corresponding value using cancer mortality-based models is essentially unchanged at around 5% per Sv.

(A 166) An additional point relating to the present detriment-adjusted cancer coefficients of Table A.4.4 is that, during the period that the present ICRP Recommendations are likely to apply, the survival rates for many cancers are expected to rise. In this respect the nominal risk coefficient proposed here will tend to be an overestimate of risks in the future.

(A 167) The differences in the estimates of detriment-adjusted heritable effects between the present report and *Publication 60* are explained and discussed in Section A.6.5.

Cancer risk following prenatal (in-utero) irradiation

(A 168) Studies on cancer risk following irradiation of the unborn child were reviewed in *Publication 90* (ICRP 2003a).

(A 169) The largest case-control study of cancer after in-utero irradiation, the Oxford Study of Childhood Cancers (OSCC), found that radiation increased all types of childhood cancer by approximately the same degree. The second largest study showed a larger relative risk of leukaemia than for solid tumours, while several cohorts studies of in-utero radiation found no clear evidence of radiation-induced childhood cancer. The limited data from the atomic bomb survivors suggest that the lifetime cancer risk from in-utero exposure may be similar to that from exposure in early childhood.

(A 170) The OSCC data suggest that cancer induction is at least as likely following exposure in the first trimester as in later trimesters. From the data published to date,

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it is not possible to determine tissue-weighting factors in order to define cancer risk in different tissues and organs. Adequate human in-utero exposure data are not available to define the dose and dose-rate effectiveness factor (DDREF) for low-LET radiation or the RBE values for neutron or other high-LET radiations.

(A 171) Given the limitations of the available data, the Commission has not attempted to derive a specific value for the nominal coefficient for life-time cancer risk after prenatal exposure, and supports the *Publication 90* (ICRP, 2003a) judgement that it is reasonable to assume that this risk is, at most, a few times that of the population as a whole. This in-utero risk is judged to be no greater than that following exposure in early childhood.

Genetic susceptibility to radiation-induced cancer

(A 172) On the basis of the data analyses and judgements developed in *Publication 79* (ICRP, 1998a) and further information reviewed by UNSCEAR (2000), UNSCEAR (2001), and the BEIR VII Committee (NAS/NRC, 2006), the Commission believes that strongly expressing, high penetrance, cancer genes are too rare to cause significant distortion of the population-based estimates of low-dose radiation cancer risk made in this Section of the report. However, as noted in *Publication 79*, there are likely to be implications for individual cancer risks, particularly for second cancers in gene carriers receiving radiotherapy for a first neoplasm. Although the Commission recognises that weakly expressing variant cancer genes may, in principle, be sufficiently common to impact upon population-based estimates of radiation cancer risk, the information available is not sufficient to provide a meaningful quantitative judgement on this issue.

The possibility of non-linear low-dose responses for cancer risk

(A 173) The emergence of new data and hypotheses frequently poses questions on the validity of scientific hypotheses and their practical applications. This is certainly the case in radiological protection and particularly for the so-called linear-non-threshold (LNT) model and the derived LNT model used for projecting cancer risk to low doses and low dose rates (UNSCEAR, 2000, CERRIE, 2004, NAS/NRC, 2006, French Academies Report 2005). As given below, there are two principal categories of challenge, both of which hypothesise non-linear low-dose responses.

(A 174) ***Supra-linear low-dose responses.*** It has been proposed by some that the radiation dose response for cancer induction has a supra-linear component at low doses (i.e., a bimodal dose-response relationship) and therefore the projection of low-dose risk from observations made at higher doses will lead to a substantial underestimate of the true risk (CERRIE 2004 and references therein). Such hypotheses are frequently cited in association with reports on unusual epidemiological and experimental observations.

(A 175) The UK CERRIE Committee (CERRIE 2004) considered the scientific validity of claims of such underestimation of cancer risk, particularly in respect of internal radiations. The claims considered were largely based upon; a) the interpretation of selected epidemiological datasets; b) biophysical proposals on the mode of action of certain internal radiations; c) the role of induced genomic instability/

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bystander signalling in cancer development; and d) the fitting of bimodal or polymodal dose-responses to epidemiological and experimental data.

(A 176) The Commission agrees with the general view expressed by the majority of CERRIE members that none of the proposals on the gross underestimation of risk that were considered have a sound scientific basis and that some are demonstrably flawed. The following points illustrate the views of the Commission:

- The epidemiological evidence cited did not provide consistent evidence that risk of childhood leukaemia from nuclear test fallout was seriously underestimated by established radiation risk models.
- The so-called Second Event Theory cited in support of higher than expected cancer risk from ^{90}Sr and particulate forms of alpha-emitters was inadequately formulated and inconsistent with a well-established body of biological data.
- The association between induced genomic instability/bystander signalling and cancer risk has yet to be established adequately (see Section A.4.1, paragraph A 97).
- The data relating to bimodal/polymodal dose responses were generally weak, the statistical analyses were inadequate, and the phenomena, if real, had no obvious mechanistic basis.

(A 177) While recognising considerable uncertainty on estimates of cancer risk at low doses, the Commission judges that the data and theories concerning supra-linear dose response do not provide evidence that the application of current cancer risk models based upon the linear-non-threshold (LNT) model and application of the concept of effective dose leads to a gross underestimate of cancer risk.

Table A.4.5. Values for lethality factors, non-fatal case weights, and relative life lost values used in the current computations, together with the corresponding values in *Publication 60*.

Site	Current			ICRP 60	
	Lethality (k)	Non-fatal case weight (q)	Relative life lost	Lethality ($k = q$)	Relative life lost
Oesophagus	0.93	0.935	0.87	0.95	0.65
Stomach	0.83	0.846	0.88	0.90	0.83
Colon	0.48	0.530	0.97	0.55	0.83
Liver	0.95	0.959	0.88	0.95	1.00
Lung	0.89	0.901	0.80	0.87	0.90
Bone	0.45	0.505	1.00	0.72	1.00
Skin	0.002	0.002	1.00	–	1.00
Breast	0.29	0.365	1.29	0.50	1.21
Ovary	0.57	0.609	1.12	0.70	1.12
Bladder	0.29	0.357	0.71	0.50	0.65
Thyroid	0.07	0.253	1.29	0.10	1.00
Bone Marrow	0.67	0.702	1.63	0.99	2.06
Other Solid	0.49	0.541	1.03	0.71	0.91
Gonads	0.80	0.820	1.32	–	1.33

k, q and the relative life lost are defined in Section A.4, paragraphs A 141 – A 148. In particular, q is taken as $q_{min} + (1 - q_{min})*k$ in the current calculations, where q_{min} is 0 for skin, 0.2 for thyroid and 0.1 for all other sites.

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(A 178) ***Dose thresholds.*** In the preceding discussion and computations it has been assumed that, at low doses and at low dose rates, site-specific cancer risk from low-LET radiation is proportional to radiation dose, consistent with the LNT model. Thus, the possibility that there might be a threshold dose, below which there would be no radiation-related cancer risk, has been ignored. The LNT model is not universally accepted as biological truth, but rather, because we do not actually know what level of risk is associated with very-low-dose exposure, it is considered to be a prudent judgement for public policy aimed at avoiding unnecessary risk from exposure.

(A 179) As discussed at length in *Publication 99* (ICRP, 2005d), the LNT model receives considerable, although not decisive, support from epidemiological studies of radiation-related cancer risk, in the sense that the risk of mortality and morbidity from all solid cancers combined in the LSS is proportional to radiation dose down to about 100 mGy, below which statistical variation in baseline risk, as well as small and uncontrollable biases, increasingly tend to obscure evidence concerning any radiation-related risk. This uncertainty is the main reason why it is generally impossible to determine, on epidemiological grounds alone, that there is, or is not, an increased risk of cancer associated with radiation exposures of the order of a few tens

Table A.4.6. Coefficients in the current cancer incidence-based ERR models.

Site	Sex	ERR per Gy at age 70 for exposure at age 30	Age at exposure: % change in ERR per decade increase	Power of attained age by which the ERR varies	F:M ratio	$P^*_{Consistency}$
All solid	M	0.35	–17%	–1.65	1.65	
	F	0.58				
Oesophagus	M	0.40	–17%	–1.65	1.65	>0.5
	F	0.65				
Stomach	M	0.23	–17%	–1.65	1.65	>0.5
	F	0.38				
Colon	M	0.68	–17%	–1.65	0.48	0.006
	F	0.33				
Liver	M	0.25	–17%	–1.65	1.65	>0.5
	F	0.40				
Lung	M	0.29	+17%	–1.65	4.77	0.09
	F	1.36				
Breast	F	0.87	0%	–2.26	–	0.37
Ovary	F	0.32	–17%	–1.65	–	>0.5
Bladder	M	0.67	–17%	–1.65	1.65	0.27
	F	1.10				
Thyroid	M	0.53	–56%	0.00	2.00	0.04
	F	1.05				
Other	M	0.22	–34%	–1.65	0.78	0.50
	F	0.17				

* P-values are for tests of the hypothesis that the age, age-at-exposure, and (where relevant) sex effects on the ERR describe the LSS data better than do those from a tissue-specific analysis. An exception arises for thyroid cancer in which case the P-value is for a test of the hypothesis that the model used in BEIR VII (NAS/NRC, 2006), which was based on results of the pooled analysis (Ron et al. 1995), adequately describes the current LSS data.

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of mSv and below. Risk estimates for such exposures are obtained through the use of mathematical models that assume a simple relationship, e.g., linear, linear-quadratic, or linear with a dose and dose rate effectiveness factor (DDREF) between risk at higher doses, where epidemiological data tend to be informative, and at doses so low that direct epidemiological observation is uninformative.

(A 180) In spite of the biological evidence supporting the LNT model with respect to the induction by ionising radiation of complex DNA damage, for which repair mechanisms in mammalian species tend to be error-prone, the possibility of a threshold for cancer induction at some unknown low dose cannot be ruled out (see Section A.4.1).

(A 181) At the molecular level, the generation of multiple DNA lesions within close spatial proximity, creating complex damage for which mammalian repair mechanisms tend to be error-prone, is believed to be the primary mechanism by which ionising radiation contributes to the induction of mutations and chromosome aberrations and hence to the pathogenesis of cancer. Such clustered damage in DNA

Table A.4.7. Coefficients in the current cancer incidence-based EAR models.

Site	Sex	Excess deaths per 10000 persons per year per Gy at age 70 for exposure at age 30	Age at exposure: % change in EAR per decade increase	Power of attained age by which the EAR varies	F:M ratio	$P^{a}_{Consistency}$
All Solid	M	43.20	−24%	2.38	1.38	
	F	59.83				
Oesophagus	M	0.48	64%	2.38	1.38	0.08
	F	0.66				
Stomach	M	6.63	−24%	2.38	1.38	>0.5
	F	9.18				
Colon	M	5.76	−24%	2.38	0.42	0.02
	F	2.40				
Liver	M	4.18	−24%	2.38	0.31	0.06
	F	1.30				
Lung	M	6.47	1%	4.25	1.38	<0.001
	F	8.97				
Breast	F	10.9	−39%	3.5*	—	0.06
				1.0		
Ovary	F	1.47	−24%	2.38	—	>0.5
Bladder	M	2.00	−11%	6.39	1.38	0.01
	F	2.77				
Thyroid	M	0.69	−24%	0.01	3.36	<0.001
	F	2.33				
Other	M	7.55	−24%	2.38	1.38	0.12
	F	10.45				

[a] P-values are for tests of the hypothesis that the age, age-at-exposure, and (where relevant) sex effects on the EAR describe the LSS data better than do those from a tissue-specific analysis. An exception arises for breast cancer, in which case the P-value is for a test of the hypothesis that the model based on the pooled analysis described by Preston et al. (2002) adequately describes the current LSS data.

[*] The upper term is the age effect before age 50 and the lower term is the effect for age greater than 50.

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can, in principle, be induced even by a single radiation track through a cell. Also, while many of the viable cells containing such radiation-induced damage may be eliminated by damage response pathways involving cell cycle checkpoint control and apoptotic cell death, it is clear from analysis of cytogenetic and mutation data that damaged or altered cells are capable of evading these protective measures and propagating.

(A 182) Recent studies using newly developed animal models of radiation tumorigenesis support the view that the essential radiation-associated events in the tumorigenic process are predominantly early events involving DNA losses targeting specific genomic regions harbouring critical genes (see Section A.2.7, paragraphs A 41 – A 44). As such, the response for early initiating events is likely to correspond to that for the induction of cytogenetic and mutagenic damage. On this basis, mechanistic arguments support a linear response in the low-dose region, i.e., the process should be independent of dose rate because interactions between different electron tracks should be rare. Quantitative analyses of dose responses for tumorigenesis and for life shortening in laboratory animals also tend to support this prediction albeit with considerable quantitative uncertainty.

(A 183) There are also long-standing arguments on whether some form of low-dose stimulation of anti-tumorigenic components of the immune system might serve to reduce cancer risk. Such proposals have been considered in depth by UNSCEAR (UNSCEAR 1993, 1994), and the Commission shares the doubts of UNSCEAR that

Table A.4.8. Coefficients in the current mortality-based ERR models.

Site	Sex	ERR per Gy at age 70 for exposure at age 30	Age at exposure: % change in ERR per decade increase	Power of attained age by which the ERR varies	F:M ratio	$P_{Consistency}$
Solid	M	0.35	−31%	−0.74	1.68	
	F	0.58				
Oesophagus	M	0.76	−31%	−0.74	1.68	0.47
	F	1.27				
Stomach	M	0.26	−31%	−0.74	1.68	0.48
	F	0.43				
Colon	M	0.25	−31%	−4.46	1.00	0.43
	F	0.25				
Liver	M	0.21	−31%	−0.74	1.68	0.94
	F	0.34				
Lung	M	0.55	−4%	−0.74	1.68	0.76
	F	0.92				
Breast	F	0.96	−31%	−0.74		0.70
Ovary	F	0.67	−31%	−0.74		0.67
Bladder	M	0.74	12%	−0.74	1.68	0.75
	F	1.24				
Other	M	0.13	−56%	−0.74	1.68	0.40
	F	0.22				

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the immune system plays a significant role in any cancer-related adaptive processes at low doses (UNSCEAR 2000).

(A 184) As discussed in *Publication 99*, the statistical uncertainty highlighted earlier in this section is accompanied by other uncertainties, on the model assumptions needed to estimate the risk of radiation-related cancer at low radiation doses. These latter uncertainties are usually subject to only subjective quantification. Such uncertain assumptions include, among others, the DDREF to be applied at low doses and low dose rates, the relationship between excess and baseline cancer rates when transferring estimates from one population to another, and the relationship between estimated and true radiation dose in the exposed population from which the risk estimate was derived (see paragraphs A 125–A 148). All of these assumptions can profoundly affect the estimated risk and its probabilistic uncertainty limits. If one also allows for the uncertain possibility of a universal threshold dose at some known level, or a threshold the value of which is highly uncertain or which varies widely among members of the exposed population, this also affects the risk estimate and its uncertainty limits. In an analysis described in*Publication 99* it was found that, unless the existence of a threshold was assumed to be virtually certain, and its possible values restricted well beyond that which can be justified on current knowledge, the effect of introducing the uncertain possibility of a threshold was equivalent to that

Table A.4.9. Coefficients in the current mortality-based EAR models.

Site	Sex	Excess deaths 10000 persons per year per Gy at age 70 for exposure at age 30	Age at exposure: % change in EAR per decade increase	Power of attained age by which the EAR varies	F:M ratio	$P_{Consistency}$
All Solid	M	28.91	−24%	3.63	1.04	
	F	29.99				
Oesophagus	M	0.98	−24%	3.63	1.00	0.42
	F	0.98				
Stomach	M	5.79	−24%	3.63	1.00	0.45
	F	5.79				
Colon	M	2.24	−24%	3.63	1.00	0.66
	F	2.24				
Liver	M	6.46	−24%	5.56	0.37	0.42
	F	2.36				
Lung	M	6.72	−24%	6.56	1.00	0.70
	F	6.72				
Breast	F	15.73	−44%	5.78[a] −2.83		0.01[b]
Ovary	F	1.40	−24%	3.63		0.90
Bladder	M	0.83	0%	8.04	1.00	0.23
	F	0.83				
Other	M	3.68	−52%	3.63	1.00	0.29
	F	3.68				

[a] Test of hypothesis that a spline in attained age is unnecessary.
[b] The upper term is the age effect before age 50 and the lower term is the effect for age greater than 50.

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Table A.4.10. Female Euro-American cancer incidence rates by age and site.

Number of cases per 100,000 persons per year

Age	All cancer	All solid	Oesophagus	Stomach	Colon	Liver	Lung	Breast	Ovary	Bladder	Thyroid	Leukaemia	Non-CLL leukaemia	CLL
0–4	18.37	10.95	0.00	0.01	0.01	0.32	0.01	0.02	0.05	0.06	0.01	6.95	6.92	0.03
5–9	9.03	5.28	0.00	0.01	0.03	0.03	0.04	0.00	0.23	0.00	0.08	3.07	3.05	0.02
10–14	10.20	6.57	0.00	0.04	0.11	0.04	0.02	0.01	0.69	0.00	0.54	2.15	2.15	0.00
15–19	17.49	11.03	0.01	0.08	0.25	0.07	0.04	0.12	1.77	0.07	1.80	2.20	2.19	0.00
20–24	29.46	21.96	0.02	0.09	0.36	0.09	0.19	1.19	2.89	0.19	3.87	1.63	1.59	0.04
25–29	51.15	43.58	0.04	0.27	0.83	0.17	0.39	7.17	4.03	0.31	5.60	1.66	1.61	0.04
30–34	83.77	76.06	0.10	0.75	1.27	0.24	1.04	23.53	5.82	0.50	6.38	1.90	1.86	0.04
35–39	137.56	129.33	0.13	1.17	3.27	0.39	3.20	54.12	9.00	0.98	7.00	2.41	2.27	0.14
40–44	227.67	215.47	0.50	2.28	6.00	0.64	8.29	107.57	13.73	1.85	7.20	3.72	3.41	0.31
45–49	372.68	355.20	1.07	3.31	11.90	1.42	20.20	183.33	24.54	4.05	8.48	4.52	3.72	0.80
50–54	540.14	512.41	2.42	5.02	21.92	2.43	40.44	243.57	34.33	7.90	8.07	7.61	5.28	2.34
55–59	703.34	663.31	5.27	8.76	41.98	4.07	67.32	263.17	41.39	13.25	7.97	9.99	6.59	3.40
60–64	907.16	851.75	7.92	14.26	63.80	6.73	106.00	298.07	49.35	22.38	7.16	15.15	9.82	5.33
65–69	1127.22	1048.58	11.24	21.99	94.46	9.82	154.72	305.57	55.60	33.45	7.79	21.91	12.96	8.94
70–74	1385.31	1279.59	16.96	33.48	138.10	14.11	190.74	328.61	62.04	47.83	8.53	30.29	17.72	12.57
75–79	1557.27	1427.72	21.52	47.53	177.76	17.32	191.05	339.09	61.42	56.59	8.13	37.99	21.96	16.03
80–84	1707.07	1565.32	26.77	65.22	234.14	22.02	166.82	365.99	56.31	68.67	8.73	43.94	26.88	17.05
85–89	1660.82	1667.88	34.82	76.14	241.25	21.66	127.96	335.97	49.39	83.68	8.73	43.98	26.91	17.07
90+	1720.81	1706.61	23.34	73.73	266.50	16.94	76.51	382.23	38.63	54.69	8.73	73.39	44.90	28.48

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Table A.4.11. Male Euro-American cancer incidence rates by age and site.

Number of cases per 100,000 persons per year

Age	All cancer	All solid	Oesophagus	Stomach	Colon	Liver	Lung	Breast	Ovary	Bladder	Thyroid	Leukaemia	Non-CLL leukaemia	CLL
0–4	21.64	12.70	0.00	0.01	0.00	0.62	0.01			0.12	0.00	7.78	7.77	0.01
5–9	11.66	6.18	0.00	0.00	0.00	0.10	0.00			0.01	0.05	3.80	3.80	0.00
10–14	12.26	6.18	0.00	0.00	0.06	0.05	0.03			0.02	0.13	3.07	3.07	0.00
15–19	18.72	11.10	0.00	0.06	0.13	0.10	0.11			0.10	0.43	2.73	2.73	0.00
20–24	29.00	20.81	0.02	0.10	0.33	0.15	0.19			0.39	0.77	1.98	1.98	0.00
25–29	43.12	32.54	0.09	0.27	0.92	0.22	0.36			0.60	1.54	2.36	2.33	0.03
30–34	58.48	45.37	0.21	0.82	1.75	0.32	0.99			1.27	1.47	2.87	2.80	0.07
35–39	77.82	61.65	0.64	1.45	3.15	0.72	3.19			2.52	1.78	3.61	3.20	0.41
40–44	115.96	95.95	1.94	3.27	6.71	2.06	9.41			5.70	2.15	4.65	3.81	0.84
45–49	198.61	170.47	4.26	6.02	12.42	3.12	23.28			12.63	2.83	6.67	4.85	1.82
50–54	380.05	337.58	9.47	11.72	25.26	5.53	56.22			25.29	3.34	11.59	7.20	4.38
55–59	676.04	617.96	15.68	21.64	47.90	9.60	108.53			46.07	3.81	16.47	9.56	6.91
60–64	1136.55	1053.31	24.79	36.02	84.67	15.00	189.00			79.67	4.16	25.34	14.06	11.28
65–69	1767.07	1651.87	33.72	58.28	129.65	22.80	304.06			132.28	5.24	37.75	20.92	16.83
70–74	2415.76	2255.06	46.59	87.72	185.35	30.88	400.78			184.53	5.69	56.29	30.97	25.33
75–79	2882.34	2680.83	49.57	114.49	248.89	36.70	456.24			229.94	5.98	68.43	39.48	28.95
80–84	3225.05	2983.09	55.88	145.00	310.36	36.96	459.96			275.56	6.26	86.36	50.15	36.21
85–89	3033.46	3166.00	59.36	165.76	316.71	37.73	404.07			266.44	6.26	91.89	38.53	53.36
90+	3676.73	3290.99	49.36	137.84	335.18	39.21	337.79			376.32	6.26	102.86	43.13	59.73

Table A.4.12. Female Euro-American cancer mortality rates by age and site.

Number of deaths per 100,000 persons per year

Age	All cause	All cancer	All solid	Oesophagus	Stomach	Colon	Liver	Lung	Breast	Ovary	Bladder	Leukaemia	Non-CLL leukaemia	CLL
0–4	114.61	2.22	1.46	0.00	0.00	0.00	0.06	0.02	0.00	0.01	0.00	0.76	0.76	0.00
5–9	11.35	2.01	1.42	0.00	0.00	0.00	0.02	0.01	0.00	0.01	0.01	0.59	0.59	0.00
10–14	13.28	2.05	1.34	0.00	0.02	0.01	0.02	0.01	0.00	0.03	0.00	0.71	0.71	0.00
15–19	28.51	2.76	1.74	0.00	0.03	0.04	0.05	0.02	0.00	0.10	0.00	1.02	1.02	0.00
20–24	33.03	3.40	2.46	0.01	0.05	0.06	0.10	0.04	0.09	0.21	0.00	0.94	0.94	0.00
25–29	40.17	5.97	5.10	0.02	0.14	0.21	0.11	0.10	0.96	0.31	0.01	0.87	0.87	0.00
30–34	55.43	12.77	11.86	0.04	0.41	0.35	0.15	0.53	3.85	0.74	0.06	0.91	0.91	0.00
35–39	81.36	26.07	24.79	0.10	0.69	1.11	0.28	1.90	9.49	1.41	0.09	1.27	1.27	0.00
40–44	122.96	48.98	47.14	0.30	1.23	2.02	0.58	5.45	18.24	3.34	0.19	1.84	1.84	0.00
45–49	193.21	88.79	86.48	0.87	1.76	4.59	1.07	13.34	31.03	7.13	0.49	2.31	2.31	0.00
50–54	309.20	150.52	147.17	1.87	2.98	8.82	1.82	28.25	45.67	13.39	1.00	3.34	3.34	0.00
55–59	489.59	232.48	227.46	3.93	5.16	16.19	3.28	48.94	57.28	21.10	1.82	5.15	5.02	0.13
60–64	801.25	343.06	335.47	6.24	8.47	25.88	5.31	81.35	68.26	27.83	3.70	7.59	7.59	0.00
65–69	1283.49	487.75	476.42	9.10	14.54	39.32	8.87	123.13	82.37	34.97	6.63	12.06	11.33	0.73
70–74	2098.33	654.11	636.96	13.79	21.54	58.94	12.40	158.51	97.91	42.39	11.95	17.97	17.15	0.83
75–79	3406.46	801.53	778.31	20.07	32.16	81.11	16.83	167.46	117.85	45.48	17.98	25.36	23.22	2.15
80–84	5934.90	988.90	956.69	26.37	47.48	118.84	21.81	159.62	146.37	47.35	29.09	35.14	32.21	2.94
85–89	9876.82	1178.13	1146.03	35.87	64.84	165.46	26.79	137.93	188.77	46.61	48.53	38.97	35.71	3.25
90+	19441.90	1220.69	1172.64	24.05	62.78	182.78	20.95	82.47	214.76	36.46	31.72	65.02	59.59	5.43

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Table A.4.13. Male Euro-American cancer mortality rates by age and site.

Number of deaths per 100,000 persons per year

Age	All cause	All cancer	All solid	Oesophagus	Stomach	Colon	Liver	Lung	Breast	Ovary	Bladder	Leukaemia	Non-CLL leukaemia	CLL
0–4	143.02	2.75	1.97	0.00	0.00	0.00	0.11	0.00			0.00	0.78	0.78	0.00
5–9	15.39	2.74	1.70	0.00	0.00	0.00	0.05	0.01			0.01	1.04	1.04	0.00
10–14	19.43	2.52	1.39	0.00	0.00	0.01	0.02	0.01			0.01	1.12	1.12	0.00
15–19	66.78	3.50	2.10	0.00	0.01	0.04	0.05	0.02			0.00	1.41	1.41	0.00
20–24	94.71	4.50	3.27	0.02	0.06	0.13	0.09	0.12			0.01	1.23	1.23	0.00
25–29	99.79	5.87	4.56	0.05	0.14	0.28	0.12	0.20			0.01	1.31	1.31	0.00
30–34	124.33	9.09	7.75	0.18	0.36	0.55	0.21	0.64			0.05	1.34	1.34	0.00
35–39	160.80	16.28	14.65	0.48	0.83	1.12	0.50	2.23			0.14	1.63	1.63	0.00
40–44	224.83	34.98	32.89	1.66	1.78	2.46	1.33	7.19			0.46	2.08	2.08	0.00
45–49	321.50	69.83	67.16	3.62	3.33	5.22	2.38	18.84			1.00	3.09	2.67	0.42
50–54	505.70	143.81	139.31	7.94	6.11	10.74	3.90	45.14			2.87	4.79	4.50	0.30
55–59	821.44	262.09	254.99	13.88	11.61	20.26	7.03	89.61			6.09	7.64	7.11	0.54
60–64	1378.11	457.53	446.19	21.98	21.78	35.75	11.69	162.02			12.33	12.85	11.34	1.51
65–69	2241.12	734.15	714.15	30.93	34.77	56.32	17.62	260.63			23.18	20.56	20.00	0.56
70–74	3590.14	1065.72	1036.77	41.20	53.11	85.62	24.51	354.10			39.44	32.65	28.94	3.70
75–79	5634.15	1427.76	1387.32	49.19	75.51	116.26	31.46	421.65			61.53	45.15	40.44	4.71
80–84	9122.79	1880.96	1826.90	55.21	103.50	165.63	36.27	464.57			96.92	64.25	54.06	10.19
85–89	13879.10	2208.86	2287.11	63.41	132.47	221.43	37.50	445.09			135.96	82.03	69.02	13.01
90+	24029.19	2677.26	2377.40	52.73	110.15	234.35	38.98	372.08			192.04	91.82	77.26	14.57

Table A.4.14. Female Asian cancer incidence rates by age and site.

Number of cases per 100,000 persons per year

Age	All cancer	All solid	Oesophagus	Stomach	Colon	Liver	Lung	Breast	Ovary	Bladder	Thyroid	Leukaemia	Non-CLL leukaemia	CLL
0–4	16.18	10.16	0.00	0.00	0.00	0.41	0.00	0.00	0.017	0.23	0.00	4.63	4.63	0.00
5–9	7.47	4.04	0.00	0.00	0.00	0.15	0.00	0.00	0.248	0.00	0.18	2.44	2.44	0.00
10–14	10.32	6.13	0.00	0.00	0.00	0.15	0.05	0.00	1.170	0.00	0.55	3.25	3.25	0.00
15–19	9.62	7.27	0.00	0.20	0.30	0.11	0.12	0.00	1.485	0.00	1.54	1.62	1.62	0.00
20–24	16.76	13.77	0.00	0.95	0.26	0.22	0.14	0.51	2.075	0.06	3.26	1.58	1.58	0.00
25–29	29.87	26.73	0.11	2.41	1.52	0.32	0.86	3.62	2.492	0.15	3.84	1.76	1.76	0.00
30–34	61.04	56.94	0.05	8.54	2.40	0.92	1.26	14.77	3.452	0.13	5.74	2.02	2.02	0.00
35–39	113.76	107.71	0.20	15.25	5.53	2.25	2.97	38.85	5.848	0.43	6.78	3.29	3.27	0.01
40–44	184.71	177.61	0.65	24.58	9.34	3.69	7.70	67.94	9.592	0.75	10.45	3.93	3.92	0.01
45–49	242.53	233.01	1.15	27.18	16.76	5.89	12.55	86.55	13.050	0.94	13.31	4.26	4.18	0.08
50–54	302.19	290.49	2.17	34.98	28.27	11.12	19.96	81.36	15.142	2.80	12.54	6.02	5.89	0.13
55–59	401.39	386.17	6.38	52.62	44.43	21.21	34.36	76.81	16.122	4.62	11.59	5.96	5.60	0.36
60–64	592.40	565.68	12.35	75.78	71.50	46.70	63.49	88.33	19.615	7.49	12.86	9.70	9.19	0.51
65–69	776.54	744.60	17.66	113.21	89.08	75.39	89.27	86.57	19.888	10.82	12.59	11.11	10.75	0.36
70–74	1017.79	974.89	28.42	159.53	126.39	84.23	145.22	84.42	20.507	18.15	13.96	15.34	14.84	0.49
75–79	1177.00	1127.05	34.69	195.44	138.59	96.89	171.64	82.73	20.268	25.43	13.00	14.35	13.56	0.79
80–84	1338.05	1279.76	38.69	260.54	152.09	111.69	176.17	82.34	15.482	35.23	11.16	19.49	18.58	0.92
85–89	1470.65	1400.73	28.65	284.69	174.60	114.47	184.59	52.17	21.20	50.41	11.16	21.61	19.69	1.91
90+	1733.18	1653.38	27.96	354.64	244.83	113.01	193.15	65.36	23.17	34.96	11.16	22.70	20.69	2.01

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Table A.4.15. Male Asian cancer incidence rates by age and site.

Number of cases per 100,000 persons per year

Age	All cancer	All solid	Oesophagus	Stomach	Colon	Liver	Lung	Breast	Ovary	Bladder	Thyroid	Leukaemia	Non-CLL leukaemia	CLL
0–4	16.69	10.30	0.00	0.08	0.00	0.74	0.03			0.03	0.00	5.17	5.09	0.08
5–9	10.73	4.54	0.00	0.05	0.00	0.24	0.05			0.00	0.02	4.73	4.73	0.00
10–14	10.72	5.48	0.00	0.06	0.06	0.33	0.07			0.00	0.23	3.31	3.31	0.00
15–19	12.15	7.20	0.00	0.33	0.10	0.13	0.14			0.06	0.59	3.51	3.51	0.00
20–24	13.97	9.68	0.00	0.81	0.50	0.70	0.41			0.31	0.74	2.30	2.30	0.00
25–29	21.59	16.88	0.10	2.29	0.91	1.67	0.51			0.59	0.99	2.94	2.89	0.05
30–34	37.04	31.17	0.13	5.05	3.54	3.60	2.30			0.81	1.16	3.55	3.49	0.06
35–39	72.78	65.58	0.80	14.96	5.45	11.41	5.09			2.20	1.67	3.03	2.93	0.10
40–44	140.70	131.55	2.94	29.51	12.43	21.68	14.83			3.59	2.15	3.90	3.71	0.19
45–49	227.28	213.75	7.05	47.43	24.55	36.58	23.27			5.14	3.17	5.45	5.30	0.15
50–54	357.46	339.23	14.35	76.73	39.96	54.82	44.64			10.69	2.82	7.01	6.67	0.34
55–59	588.80	564.44	25.49	127.25	72.34	95.29	80.55			17.08	2.86	9.51	9.07	0.43
60–64	1059.95	1019.71	44.55	217.15	119.83	170.87	176.67			33.03	3.84	13.36	12.55	0.81
65–69	1523.88	1468.59	58.10	316.67	162.08	195.63	317.21			55.42	5.13	20.21	18.61	1.60
70–74	1948.97	1878.15	82.63	412.58	186.30	192.09	439.32			73.66	5.16	27.13	25.46	1.67
75–79	2267.27	2180.80	92.66	488.08	214.56	183.31	509.83			108.13	4.68	30.62	28.83	1.79
80–84	2470.31	2375.91	94.17	520.98	222.27	187.30	540.57			120.05	4.35	31.68	28.87	2.81
85–89	3372.14	3223.64	69.75	716.89	326.54	232.57	682.18			158.97	4.35	49.11	44.17	4.94
90+	3907.81	3742.07	68.97	863.48	422.02	215.09	608.83			264.33	4.35	49.86	44.84	5.02

Table A.4.16. Female Asian cancer mortality rates by age and site.

Number of deaths per 100,000 persons per year

Age	All cause	All cancer	All solid	Oesophagus	Stomach	Colon	Liver	Lung	Breast	Ovary	Bladder	Leukaemia	Non-CLL leukaemia	CLL
0–4	127.18	3.38	1.70	0.00	0.01	0.00	0.10	0.02	0.00	0.01	0.01	1.34	1.34	0.00
5–9	16.67	3.08	1.33	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.00	1.33	1.33	0.00
10–14	15.15	3.52	1.42	0.01	0.00	0.01	0.05	0.00	0.01	0.04	0.00	1.66	1.66	0.00
15–19	18.31	3.39	1.46	0.02	0.07	0.04	0.08	0.04	0.01	0.13	0.01	1.24	1.24	0.00
20–24	27.75	3.97	2.31	0.01	0.28	0.17	0.20	0.16	0.08	0.19	0.00	1.16	1.16	0.00
25–29	33.29	6.37	4.66	0.04	0.89	0.39	0.40	0.38	0.36	0.20	0.01	1.15	1.15	0.00
30–34	44.91	13.20	11.14	0.06	2.28	1.02	0.98	1.06	1.67	0.52	0.04	1.43	1.43	0.00
35–39	62.83	23.88	21.06	0.15	4.13	1.95	1.79	2.27	4.58	1.24	0.06	1.79	1.79	0.00
40–44	107.45	45.04	41.40	0.46	7.14	3.39	3.74	5.45	8.89	2.26	0.09	2.32	2.32	0.00
45–49	162.17	66.72	62.51	1.26	9.31	5.26	6.20	9.08	12.01	4.36	0.16	2.65	2.65	0.00
50–54	237.87	94.83	90.12	2.16	12.01	7.43	9.43	15.19	14.91	6.52	0.38	2.71	2.57	0.14
55–59	399.63	151.41	144.12	4.31	19.77	12.43	15.91	29.64	17.01	6.21	0.81	3.65	3.57	0.08
60–64	740.16	245.00	234.08	8.43	30.60	20.91	28.82	54.90	17.67	9.05	1.45	5.44	5.26	0.18
65–69	1239.84	357.21	342.78	15.26	47.37	30.14	41.39	83.63	18.97	9.55	3.27	6.05	5.32	0.72
70–74	2184.11	508.02	488.66	25.09	73.47	46.13	57.19	115.76	20.60	10.22	6.20	8.56	7.23	1.33
75–79	3682.84	653.04	630.76	34.41	101.60	64.40	67.38	138.34	24.32	11.85	10.27	8.60	7.58	1.02
80–84	6509.31	780.83	755.96	37.66	134.47	82.36	73.27	148.97	31.19	9.55	15.88	9.19	8.56	0.63
85–89	8923.98	712.91	693.30	39.96	126.81	75.93	63.03	119.29	29.99	8.63	21.78	6.95	6.71	0.23
90+	17750.63	840.17	818.35	39.00	157.96	106.46	62.23	124.82	37.57	9.43	15.10	7.30	7.05	0.25

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Table A.4.17. Male Asian cancer mortality rates by age and site.

Number of deaths per 100,000 persons per year

Age	All cause	All cancer	All solid	Oesophagus	Stomach	Colon	Liver	Lung	Breast	Ovary	Bladder	Leukaemia	Non-CLL leukaemia	CLL
0–4	149.24	3.79	1.75	0.00	0.00	0.01	0.15	0.02			0.02	1.60	1.60	0.00
5–9	24.88	3.96	1.62	0.00	0.00	0.01	0.08	0.01			0.00	1.77	1.77	0.00
10–14	23.65	4.78	2.00	0.00	0.01	0.01	0.10	0.01			0.00	1.98	1.98	0.00
15–19	35.16	4.81	2.20	0.00	0.09	0.05	0.18	0.09			0.01	1.66	1.66	0.00
20–24	50.43	5.06	2.87	0.02	0.25	0.19	0.47	0.22			0.02	1.44	1.44	0.00
25–29	59.21	7.79	5.40	0.06	0.62	0.37	1.36	0.59			0.03	1.46	1.46	0.00
30–34	80.39	14.60	11.97	0.17	1.67	0.91	3.75	1.70			0.04	1.74	1.74	0.00
35–39	114.64	29.41	25.77	0.48	3.83	1.99	8.34	4.17			0.14	2.13	2.12	0.00
40–44	188.22	58.32	53.62	2.13	8.05	3.58	17.40	9.85			0.25	2.61	2.55	0.06
45–49	276.69	95.90	90.33	5.09	14.22	5.43	26.64	18.17			0.57	3.03	2.59	0.44
50–54	399.85	149.26	141.77	9.83	23.38	8.45	36.85	31.35			1.04	3.48	2.97	0.51
55–59	646.43	252.16	242.34	17.39	42.54	14.49	55.24	58.84			2.09	4.85	4.73	0.12
60–64	1257.04	482.58	466.03	34.20	80.47	28.65	95.25	130.56			5.07	6.98	6.33	0.65
65–69	2107.53	755.18	732.35	54.58	130.26	43.47	118.07	230.26			11.07	10.31	9.74	0.57
70–74	3550.26	1065.73	1035.03	82.96	194.71	65.39	131.80	335.02			19.49	13.49	12.52	0.97
75–79	5749.87	1365.66	1325.91	102.71	259.01	90.86	142.09	409.23			37.80	16.55	15.52	1.02
80–84	9661.98	1661.07	1614.41	121.87	328.69	122.29	155.29	446.43			62.69	18.78	16.66	2.12
85–89	12799.94	1586.63	1542.42	121.60	307.77	128.12	137.19	397.35			73.45	19.76	18.03	1.74
90+	22367.18	1838.67	1790.47	120.24	370.70	165.59	126.88	354.63			122.13	20.06	18.30	1.76

of an uncertain increase in the value of DDREF, i.e., merely a variation on the result obtained by ignoring the possibility of a threshold.

(A 185) The existence of a low-dose threshold for cancer induction in certain tissues is not implausible. Indeed, as noted in *Publication 99* there is no clear evidence for a radiation-associated excess of cancers for a number of human tissues, e.g., chronic lymphocytic leukaemia, testicular cancer, and melanoma skin cancer.

Table A.4.18. Estimates of sex-specific population detriments for ages 0–85 years at exposure.

Tissue	Nominal risk coefficient (cases per 10,000 persons per Sv)	Lethality fraction	Lethality-adjusted nominal risk* (relating to column 1)	Relative cancer-free life lost	Detriment (relating to column 1)	Relative detriment[a]
Male						
Oesophagus	15	0.93	14	0.87	12.6	0.026
Stomach	68	0.83	66	0.88	57.9	0.120
Colon	91	0.48	69	0.97	66.8	0.138
Liver	41	0.95	41	0.88	36.1	0.075
Lung	76	0.89	75	0.80	59.9	0.124
Bone	7	0.45	5	1.00	5.1	0.011
Skin	1000	0.002	4	1.00	4.0	0.008
Breast	0	0.29	0	1.29	0.0	0.000
Ovary	0	0.57	0	1.12	0.0	0.000
Bladder	46	0.29	25	0.71	17.5	0.036
Thyroid	12	0.07	4	1.29	4.8	0.010
Bone marrow	48	0.67	43	1.63	69.8	0.144
Other solid	157	0.49	120	1.03	123.9	0.256
Gonads (heritable)	20	0.80	19	1.32	25.4	0.053
Total	***1580***		***485***		***483.9***	***1.00***
Female						
Oesophagus	16	0.93	16	0.87	13.6	0.021
Stomach	91	0.83	88	0.88	77.5	0.117
Colon	40	0.48	30	0.97	29.0	0.044
Liver	19	0.95	19	0.88	17.0	0.026
Lung	153	0.89	151	0.80	120.7	0.182
Bone	7	0.45	5	1.00	5.1	0.008
Skin	1000	0.00	4	1.00	4.0	0.006
Breast	224	0.29	124	1.29	159.7	0.240
Ovary	21	0.57	18	1.12	19.8	0.030
Bladder	41	0.29	22	0.71	15.8	0.024
Thyroid	53	0.07	16	1.29	20.6	0.031
Bone marrow	36	0.67	33	1.63	53.2	0.080
Other solid	131	0.49	100	1.03	103.1	0.155
Gonads (heritable)	20	0.80	19	1.32	25.4	0.038
Total	***1851***		***645***		***664.6***	***1.00***

[a] Estimates based on cancer incidence data. These sex-specific values for detriment do not have specific functions in the Commission's system of radiological protection (see paragraph A 156).

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Table A.4.19. Estimates of sex-specific population detriments for ages 18–64 years at exposure.

Tissue	Nominal risk coefficient (cases per 10,000 persons per Sv)	Lethality fraction	Lethality-adjusted nominal risk* (relating to column 1)	Relative cancer-free life lost	Detriment (relating to column 1)	Relative detriment[a]
Male						
Oesophagus	14	0.93	14	0.91	12.8	0.035
Stomach	51	0.83	50	0.89	44.5	0.122
Colon	73	0.48	55	1.13	62.0	0.170
Liver	31	0.95	31	0.93	28.5	0.078
Lung	84	0.89	83	0.96	80.0	0.219
Bone	5	0.45	3	1.00	3.4	0.009
Skin	670	0.002	3	1.00	2.7	0.007
Breast	0	0.29	0	1.20	0.0	0.000
Ovary	0	0.57	0	1.16	0.0	0.000
Bladder	40	0.29	22	0.85	18.6	0.051
Thyroid	4	0.07	1	1.19	1.6	0.004
Bone Marrow	24	0.67	22	1.17	25.2	0.069
Other Solid	94	0.49	72	0.97	70.1	0.192
Gonads (Heritable)	12	0.80	12	1.32	15.3	0.042
Total	***1103***		***368***		***365***	***1.00***
Female						
Oesophagus	16	0.93	16	0.91	14.4	0.028
Stomach	70	0.83	68	0.89	60.7	0.119
Colon	33	0.48	25	1.13	27.7	0.054
Liver	16	0.95	16	0.93	14.7	0.029
Lung	174	0.89	172	0.96	165.4	0.325
Bone surface	5	0.45	3	1.00	3.4	0.007
Skin	670	0.002	3	1.00	2.7	0.005
Breast	116	0.29	64	1.20	76.6	0.150
Ovary	16	0.57	14	1.16	15.7	0.031
Bladder	39	0.29	21	0.85	17.7	0.035
Thyroid	20	0.07	6	1.19	7.0	0.014
Bone Marrow	22	0.67	20	1.17	22.9	0.045
Other Solid	88	0.49	67	0.97	65.1	0.128
Gonads (Heritable)	12	0.80	12	1.32	15.3	0.030
Total	***1242***		***505***		***509***	***1.00***

These sex-specific values for detriment do not have specific functions in the Commission's system of radiological protection (see paragraph A 156).

[a] Estimates based on cancer incidence data.

(A 186) Although the available data do not exclude the existence of a universal low-dose threshold, the evidence as a whole, as interpreted and summarised in this Annex, does not favour this proposition. The BEIR VII Committee (NAS/NRC, 2006) has recently published a report on low-dose risk that essentially arrives at the same conclusion based on epidemiological and biological data. However, an

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equally recent low-dose report from the French Academies (2005) emphasises evidence on the potential dose-dependence of post-irradiation cellular signalling, DNA repair, apoptosis and other adaptive anti-tumorigenic processes in order to argue for the existence of a practical low-dose threshold for radiation cancer risk. Overall, the long standing question on the true validity of the LNT model may well prove to be beyond definitive scientific resolution and that 'weight of evidence' arguments and practical judgements are likely to continue to apply in the foreseeable future.

(A 187) In summary, the Commission judges that there are at present no good scientific reasons to include the possibilities of supra-linear dose responses or of a low-dose threshold in cancer risk calculations for the purposes of radiological protection. On this basis it is recommended that the LNT model, combined with a judged value of DDREF for extrapolation from high doses, remains a prudent basis for the practical purposes of radiological protection at low doses and low dose rates.

A.4.5. Further details of the detriment calculations

(A 188) In this Section, the model parameters used for the Commission's risk model are provided in detail. Table A.4.5 lists the lethality factors, non-fatal case weights, and relative life lost for the various sites considered. Tables A.4.6 and A.4.7 show coefficients in the current cancer incidence-based ERR and EAR models, respectively, while Tables A.4.8 and A.4.9 show coefficients in the current cancer mortality-based ERR and EAR models. Female and male Euro-American cancer incidence rates by age and site are given in Tables A.4.10 and A.4.11, and female and male Euro-American cancer mortality rates are given in Tables A.4.12 and A.4.13. Tables A.4.14 and A.4.15 show Asian female and male cancer incidence rates, and Tables A.4.16 and A.4.17 provide Asian female and male cancer mortality rates.

A.4.6. Estimates of sex-specific population detriments

(A 189) This Section provides estimates of sex-specific detriments, based on cancer incidence data, for ages 0–85 years at exposure in Table A.4.18 and for ages 18–64 years at exposure in Table A.4.19. The Commission emphasises that these sex-specific values for detriment have no specific function in its system of radiological protection (see paragraph A 156).

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A.5. Non-cancer diseases after radiation exposure

(A 190) Since 1990 evidence has accumulated that the frequency of non-cancer diseases is increased in irradiated populations. The strongest evidence for the induction of these non-cancer effects at doses of the order of 1 Sv derives from the A-bomb LSS, and the most recent mortality analysis (Preston et al., 2003) has strengthened the statistical evidence for an association with dose – particularly for heart disease, stroke, digestive disorders and respiratory disease. However, the Commission notes current uncertainties on the shape of the dose response at low doses and that the LSS data are consistent both with there being no dose threshold for risks of disease mortality and with a threshold of around 0.5 Sv. It is unclear what forms of cellular/tissue mechanisms might underlie such a diverse set of non-cancer disorders reported among the LSS data although some association with subclinical inflammation (e.g., Hayashi et al., 2003) is possible.

(A 191) Additional evidence of the non-cancer effects of radiation, albeit at high doses, comes from studies of cancer patients receiving radiotherapy. Studies of patients treated for Hodgkin's disease (e.g., Hancock et al. 1993, Aleman et al. 2003) and for breast cancer (e.g., Early Breast Cancer Trialists Collaborative Group 2000) have shown raised risks of mortality from cardiovascular disease, associated with doses of several tens of Gy. The situation at lower doses is less clear. A review of published epidemiological data of groups with medical or occupational exposures, which compared the rates of circulatory disease in irradiated and non-irradiated individuals drawn from the same population, concluded that there was no clear evidence of an increased risk in the majority of studies over the dose range 0 to 4 Sv (McGale and Darby 2005). Interpretation of many studies was, however, complicated by the very limited dose response data available and by a lack of information on possible confounding factors such as smoking.

(A 192) Whilst recognising the potential importance of these observations on non-cancer diseases, the Commission judges that the data available do not allow for their inclusion in the estimation of detriment following radiation doses in the range up to around 100 mSv. This agrees with the conclusion of UNSCEAR (2008), which found little evidence of any excess risk below 0.5 Sv.

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A.6. Risks of heritable diseases

A.6.1. Introduction

(A 193) The term 'genetic risks' as used in this document denotes the probability of harmful genetic effects manifest in the descendants of a population that has sustained radiation exposures. These effects are expressed as increases over the baseline frequencies of genetic diseases in the population per unit dose of low-LET, low-dose/chronic irradiation.

(A 194) Since the publication of the 1990 Recommendations of the ICRP (ICRP, 1991b), the 1990 BEIR report (NRC, 1990), and the UNSCEAR (1993) report, several important advances have been made in the prediction of genetic risks of exposure of human populations to ionising radiation. On the basis of these, UNSCEAR (2001) revised its earlier risk estimates. The aim of this section of the report is to provide a brief background on the available information and the methods that are used for risk estimation, to summarise the recent advances, to present the revised risk estimates, and to indicate how the new estimates can be used to derive a risk coefficient for genetic effects.

A.6.2. Background information

Naturally occurring genetic diseases

(A 195) The genetic diseases of interest in the present context are those due to mutations in single genes (Mendelian diseases) and those which are due to multiple genetic and environmental factors (multifactorial diseases). Historically, UNSCEAR, the BEIR Committees, and ICRP had also considered an additional class of genetic diseases, namely, chromosomal diseases which are due to gross structural and numerical abnormalities of chromosomes.

(A 196) *Mendelian diseases* are further subdivided into autosomal dominant, autosomal recessive, and X-linked recessive categories depending on the chromosomal location (autosomes or the X-chromosome) of the mutant genes and their transmission patterns. In the case of an autosomal dominant disease, a single mutant gene inherited from either parent (i.e., in a heterozygous state) is sufficient to cause disease (e.g., achondroplasia, neurofibromatosis, Marfan syndrome, etc.). The somewhat unusual genetics of dominantly inherited cancer predisposition are discussed in *Publication 79* (ICRP, 1998a). Autosomal recessive diseases, however, require two mutant genes, one from each parent, at the same locus (i.e., homozygosity) for disease manifestation (e.g., cystic fibrosis, haemochromatosis, Bloom syndrome, ataxia telangiectasia, etc.). In the case of X-linked recessive diseases, since males have only one X-chromosome, usually only males are affected (e.g., haemophilia, Duchenne muscular dystrophy, Fabry disease, etc.). However, some X-linked dominant diseases are also known (e.g., Rett syndrome), but, for the purpose of the present document, they are included under X-linked recessive diseases. The important general point with respect to Mendelian diseases is that the relationship between mutation and disease is simple and predictable.

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(A 197) *Multifactorial diseases* are aetiologically complex and consequently the relationship between mutation and disease is also complex, i.e., these do not show Mendelian patterns of inheritance. The two subgroups that constitute multifactorial diseases are the common congenital abnormalities (e.g., neural tube defects, cleft lip with or without cleft palate, congenital heart defects, etc.) and chronic diseases of adults (e.g., coronary heart disease, essential hypertension, diabetes mellitus, etc.). Evidence for a genetic component in their aetiology comes from family and twin studies which show that the first-degree relatives of affected individuals have a higher risk of disease than matched controls. For most of them, knowledge of the genes involved, the types of mutational alterations, and the nature of environmental factors still remains limited. Among the models used to explain the inheritance patterns of multifactorial diseases and estimate recurrence risks in relatives is the multifactorial threshold model (MTM) of disease liability. This is considered in a later section.

(A 198) Chromosomal diseases arise as a result of gross numerical (e.g., Down syndrome due to trisomy for chromosome 21) or structural abnormalities of chromosomes (e.g., Cri du chat syndrome due to deletion of part or whole short arm of chromosome 5) generally detectable in cytological preparations of cells. This is really not an aetiological category and, further, deletions (microscopically detectable or not) are now known to contribute to a number of genetic diseases grouped under autosomal dominant, autosomal recessive and X-linked diseases.

The doubling dose method

(A 199) In the absence of human data on radiation-induced genetic diseases, all the methods that have been developed and used since the mid 1950s up to the present are indirect; their aim is to make the best use of mutation data obtained in radiation studies with mice, data on baseline frequencies of genetic diseases in the population, and population genetic theory, to predict the radiation risk of genetic diseases in humans. One such method that has been used from the early 1970s onwards until now (e.g., UNSCEAR 2001) is the doubling dose method. This method enables one to express the expected increase in the frequencies of genetic diseases in terms of their baseline frequencies using the following equation:

$$\text{Risk per unit dose} = \text{P} \times [1/\text{DD}] \times \text{MC} \qquad \text{(A.6.1)}$$

where P is the baseline frequency of the genetic disease class under study, DD is the doubling dose (and [1/DD] is the relative mutation risk per unit dose), and MC is the disease-class-specific mutation component.

(A 200) The genetic theory that underlies the use of the DD method for risk estimation is what is referred to as the equilibrium theory which population geneticists use to explain the dynamics of mutant genes in populations. The theory postulates that the stability of mutant gene frequencies (and thus of disease frequencies) in a population is the result of the existence of a balance between the rate at which spontaneous mutations enter the gene pool of the population in every generation and the rate at which they are eliminated by natural selection, i.e., through failure of survival or reproduction. Under normal conditions (i.e., in the absence of radiation expo-

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sures), the population is assumed to be in equilibrium between mutation and selection.

(A 201) When the mutation rate is increased as a result of radiation, say, in every generation, the balance between mutation and selection is disturbed by the influx of induced mutations, but the prediction is that the population will eventually attain a new equilibrium (over a number of generations) between mutation and selection. The amount of increase in mutation frequency, the time it takes for the population to reach the new equilibrium, and the rate of approach to it are all dependent on induced mutation rates, the intensity of selection, the type of genetic disease, and whether radiation exposure occurs in one generation only or generation after generation. Worth mentioning here is that, since the starting population (before radiation exposure) is assumed to be in equilibrium between mutation and selection, the quantity P in Eqn. (A.6.1) represents the equilibrium incidence.

(A 202) *Doubling dose*. The doubling dose (DD) is the amount of radiation that is required to produce as many mutations as those that arise spontaneously in a generation. Ideally, it is estimated as a ratio of the average rates of spontaneous and induced mutations in a given set of genes.

(A 203) The reciprocal of the DD (i.e., [1/DD]) is the relative mutation risk (RMR) per unit dose. Since RMR is a fraction, the smaller the DD, the higher is the RMR and vice versa.

(A 204) *Mutation component*. Formally defined, mutation component (MC) is the relative increase in disease frequency per unit relative increase in mutation rate:

$$\mathrm{MC} = [\Delta P/P]/[\Delta m/m] \qquad \text{(A.6.2)}$$

where P is the baseline disease frequency, ΔP its change due to Δm change in mutation rate, and m the spontaneous mutation rate. The procedures used for estimating MC are relatively straightforward for autosomal dominant and X-linked diseases, slightly complicated for autosomal recessives (since an induced recessive mutation does not precipitate a recessive disease in the immediate post-radiation generations) and more complex for multifactorial diseases, and depends on the model that is used to explain their stable frequencies in the population.

A.6.3. Recent advances in understanding

(A 205) The advances that have been made during the past few years include: a) an upward revision of the estimates of the baseline frequencies of Mendelian diseases; b) the introduction of a conceptual change in the calculation of the DD; c) the elaboration of methods for estimating MC for Mendelian and chronic diseases; d) the introduction of an additional factor called the 'potential recoverability correction factor' (PRCF) in the risk equation to bridge the gap between the rates of radiation-induced mutations in mice and the risk of radiation-inducible genetic disease in human live births; and e) the introduction of the concept that the adverse effects of radiation-induced genetic damage in humans are likely to be manifest predominantly as multisystem developmental abnormalities in the progeny. All these have been discussed in detail in a series of recent publications (Chakraborty et al. 1998,

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Denniston et al. 1998, Sankaranarayanan 1998, 1999, Sankaranarayanan and Chakraborty 2000a, 2000b, 2000c, Sankaranarayanan et al. 1994, 1999, NAS/NRC 2006). Box 2 summarises the procedures used by the Commission to estimate radiation risk for heritable disease which take account of these advances in understanding.

Baseline frequencies of genetic diseases

(A 206) Until the 1993 UNSCEAR report, the baseline frequencies used in risk estimation were based on those compiled by Carter (1977) for Mendelian diseases, by UNSCEAR (1977) for chromosomal diseases, by Czeizel and Sankaranarayanan (1984) for congenital abnormalities, and by Czeizel et al. (1988) for chronic diseases. While the estimates for the last three groups of diseases have remained unchanged, those for Mendelian diseases have now been revised upwards (Sankaranarayanan, 1998). Both the earlier and the current estimates (the latter used in UNSCEAR, 2001) are presented in Table A.6.1.

Box A.2. Steps in estimating radiation risk for heritable diseases.

a) Establish the baseline frequencies of human genetic diseases of all classes (a set of values of P).
b) Estimate average spontaneous mutation rate per generation for human genes.
c) No human data available, so estimate average rate of radiation-induced mutations in mice – assume that mouse rates are similar to those of humans.
d) From b) and c) above, estimate the genetic doubling dose (DD). DD is the radiation dose required to produce as many mutations as those that arise spontaneously in one generation.
e) Estimate the mutation component (MC) for different classes of genetic diseases. MC is a relative measure of the relationship between change in mutation rate and increase in disease frequency.
f) Estimate the potential recoverability correction factor (PRCF) for different classes of mutation. PRCF allows for differing degrees of recoverability of mutations in live births, i.e., the fraction of mutations that is compatible with embryonic/fetal development.
g) For each class of human genetic disease complete the following equation using the estimates from a) to f) above.

$$\textbf{Risk per unit dose} = \mathbf{P} \times [\mathbf{1/DD}] \times \mathbf{MC} \times \mathbf{PCRF}$$

The doubling dose

(A 207) ***A re-examination of the assumptions involved in using the DD based on mouse data for risk estimation.*** The DD used until the 1993 UNSCEAR report was 1 Gy (for chronic, low-LET radiation conditions) and was based entirely on mouse data on spontaneous and induced rates of recessive mutations in seven genes.

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Table A.6.1. Baseline frequencies of genetic diseases in human populations.

Disease class	Baseline frequencies (per cent of live births)	
	UNSCEAR (1993)	UNSCEAR (2001)
Mendelian		
Autosomal dominant	0.95	1.50
X-linked	0.05	0.15
Autosomal recessive	0.25	0.75
Chromosomal	0.40	0.40
Multifactorial		
Chronic diseases	65.00[a]	65.00[a]
Congenital abnormalities	6.00	6.00

[a] Population frequency.

One of the assumptions underlying the use of mouse-data-based DD for risk estimation is that both the spontaneous and induced mutation rates in mice and humans are the same. The assumption regarding induced rates of mutations, while unavoidable, is defensible on the grounds of generally similar gene organisation, 70–90% homology in DNA sequence of genes, and substantial conservation of synteny for many (although not all) chromosomal regions in both the species. However, the situation is different with respect to spontaneous mutation rates.

(A 208) Arguments supporting the view that the spontaneous mutation rates in mice and humans are unlikely to be similar have been discussed (Sankaranarayanan, 1998, Sankaranarayanan and Chakraborty, 2000a, UNSCEAR, 2001). Briefly, unlike in the mouse, in humans there are pronounced sex-differences in spontaneous mutation rates (being higher in males than in females), and the mutation rate increases with the age of the father (paternal age effect). These differences when considered along with the fact that the human lifespan is longer than that of the mouse, suggest that extrapolating from the short-lived mouse to humans is unlikely to provide a reliable average spontaneous rate in a heterogeneous human population of all ages. Additionally, recent analyses of mouse data on mutations that arise as germinal mosaics (which result in clusters of identical mutations in the following generation) have introduced considerable uncertainty about the spontaneous mutation rate in the mouse (Selby, 1998).

(A 209) ***The use of human data on spontaneous mutation rates and mouse data for induced mutation rates for DD calculations.*** In view of the reasons stated in the preceding paragraphs, UNSCEAR (2001) considered it prudent to base DD calculations on human data on spontaneous mutation rates, and mouse data on induced mutation rates, as was first done in the 1972 BEIR report (NRC 1972). The advantages of using human data in DD calculations are: a) they pertain to human disease-causing genes; b) the mutation rate estimates in humans, because they are averaged over the sexes, automatically include paternal age effects; and c) in estimating mutation rates, human geneticists count all mutations irrespective of whether they are part of a cluster or not; consequently, had clusters occurred, they would have been included.

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(A 210) ***Average spontaneous mutation rate for human genes.*** For calculating an average spontaneous mutation rate for human genes, UNSCEAR (2001) focused on published data on those genes for which estimates of selection coefficient(*s*) were also available, the reason being that selection coefficients are relevant for estimating MC (to be discussed in the next section). Further, only autosomal dominant diseases, but not X-linked ones, were included in the analysis, the rationale being that: a) among Mendelian diseases, autosomal dominants constitute the most important group from the standpoint of genetic risks; b) while X-linked diseases are also expected to respond directly to an increase in mutation rate, their incidence in the population is an order of magnitude lower than that of autosomal dominants (0.15% versus 1.50%); and, consequently, c) the assumption of similar average mutation rates for these two classes of disease in the context of risk estimation is unlikely to result in an underestimate of the risk.

(A 211) The average (unweighted) spontaneous mutation rate based on a total of 26 autosomal dominant disease phenotypes (which, on current knowledge, relate to mutations in an estimated 135 genes) was $(2.95 \pm 0.64)\ 10^{-6}$ gene^{-1} generation^{-1} (Sankaranarayanan and Chakraborty 2000a). This estimate is well within the range of $0.5\ 10^{-5}$ to $0.5\ 10^{-6}$ per gene assumed in the 1972 BEIR report (NRC 1972). The data used for spontaneous mutation rate calculations also permit an estimate of 0.294 for average selection coefficient(s) associated with these diseases.

(A 212) ***Average rate of induced mutations in mice.*** As mentioned earlier, until the 1993 UNSCEAR report, the average rate of induced mutations used in DD calculations was based on data from studies of recessive specific locus mutations in seven genes. In the 2001 report, however, UNSCEAR expanded the database to include not only the above, but also data from studies of enzyme activity mutations, as well as dominant mutations at four loci (*Sl*, *W*, *Sp* and *T*). All these data come from studies of males in which the irradiated germ cell stages were stem-cell spermatogonia (the relevant germ cell stages in males from the standpoint of risks). The data from studies with female mice were not used since, as discussed in the 1988 UNSCEAR report, there is uncertainty as to whether the mouse immature oocytes (with nearly zero sensitivity to mutation induction after acute as well as chronic irradiation) would provide a good model for assessing the mutational radiosensitivity of human immature oocytes that are the relevant germ cell stages in the females. For the purpose of risk estimation, to err on the side of caution, it was assumed that the induced rates in females will be the same as those in males.

(A 213) Details of the data used are discussed in the UNSCEAR, 2001 report and by Sankaranarayanan and Chakraborty (2000a). The average induced mutation rate, based on mutations recovered at a total of 34 mouse genes, is $(1.08 \pm 0.30)\ 10^{-5}$ gene^{-1} Gy^{-1} for acute X or γ irradiation. With a dose-rate reduction factor of 3 traditionally used, the rate for chronic irradiation conditions becomes (0.36 ± 0.10) 10^{-5} gene^{-1} Gy^{-1}.

(A 214) ***The doubling dose.*** With the revised estimates for average spontaneous mutation rate $(2.95 \pm 0.64)\ 10^{-6}$ gene^{-1} generation^{-1} for human genes and for average rate of induced mutations $(0.36 \pm 0.10)\ 10^{-5}$ gene^{-1} Gy^{-1} for mouse genes, the

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new DD becomes (0.82 ± 0.29) Gy. This estimate, however, is not very different from 1 Gy that has been used thus far but which was based entirely on mouse data.

(A 215) UNSCEAR (2001) has suggested the continued use of the 1 Gy estimate in order to avoid the impression of undue precision, but noting that a conceptual change has now been made (i.e., use of human data on spontaneous and mouse data on induced mutation rates) and that the present estimate is supported by more extensive data than had been the case thus far. The Commission supports the UNSCEAR judgement and therefore ICRP retains a DD value of 1 Gy.

Mutation component

(A 216) As noted in Section A.6.2, the quantity 'mutation component' (MC) used in Eqn. (A.6.1) provides a measure of the relative change in disease frequency per unit relative change in mutation rate for the different classes of genetic diseases. The elements of the basic MC concept were introduced already in the 1972 BEIR report (NRC, 1972) and were subsequently considered in the papers of Crow and Denniston (1981, 1985). Within the framework of an ICRP Task Group, set up in 1993, the problem was studied in detail, and the concept, theory, methods for estimation, and algebraic formulations were fully elaborated for both Mendelian and multifactorial diseases. The Task Group report has since been published (*Publication 83*, ICRP, 1999b). The methods developed in that document now enable the evaluation of the magnitude of the MC for any post-radiation generation of interest, after either a one-time or a permanent increase in mutation rate, i.e., radiation exposure in every generation. In what follows, a brief summary of the main findings is presented.

(A 217) ***Mutation component for autosomal dominant diseases.*** For autosomal dominant diseases (for which the relationship between mutation and disease is straightforward) the estimation procedure is relatively simple. For a one-generation radiation exposure which produces a one-time increase in mutation rate ('burst', indicated by the subscript 'b' in MC_b below), the change with time 't' (in generations) is given by the equation:

$$MC_b(t) = s(1 - s)^{t-1} \qquad (A.6.3)$$

For radiation exposure to many successive generations producing a permanent increase in mutation rate (indicated by the subscript 'p'),

$$MC_p(t) = [1 - (1 - s)^t] \qquad (A.6.4)$$

(A 218) Equations (A.6.3) and (A.6.4) show that $MC_b = MC_p = s$ for the first post-radiation generation following either a one-time or a permanent increase in mutation rate. With no further irradiation in subsequent generations, the value of MC will decay back to zero at a rate of $(1 - s)$ per generation. With a permanent increase in mutation rate, however, the MC value will slowly increase to 1 at the new equilibrium. Consistent with these changes in MC, for a one-time irradiation scenario, the disease frequency will show a transitory increase in the first generation, but over time, reach the earlier or 'old' equilibrium value; for a permanent increase in mutation rate, the disease frequency will continue to increase until the new equilibrium

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value of MC = 1 is reached. At the new equilibrium, an x% increase in mutation rate will result in an x% increase in disease frequency.

(A 219) ***Mutation component for X-linked and autosomal recessive diseases.*** For X-linked diseases, for a one-time increase in mutation rate, the first generation MC = s, as in the case of autosomal dominants, but the s value needs to be adjusted to take into account the fact that only one-third of the total X-chromosome complement is in males. The dynamics of change in MC in subsequent generations is similar to that for autosomal dominants. For autosomal recessives, MC in the first generation is close to zero (consistent with the fact that an autosomal recessive mutation does not result in disease in the first generation).

(A 220) With a permanent increase in mutation rate, for both kinds of diseases, MC progressively increases to reach a value of 1 at the new equilibrium, but the rates of approach to the new equilibrium are different and are dictated by s values and time (in generations) following irradiation. In particular, for autosomal recessive diseases, the rate of approach to the new equilibrium is very slow and much slower than that for autosomal dominants and X-linked diseases.

(A 221) The important point that emerges from the above discussion is that MC is related to s and therefore, given s, one can estimate the dynamics of increase in MC and in disease frequencies for any post-radiation generation of interest. As mentioned in paragraph (A 211), the average selection coefficient estimated from data on naturally occurring autosomal dominant diseases is 0.294. This value, rounded to 0.30, is the one used as the best estimate for MC for autosomal dominant and X-linked diseases.

(A 222) ***Mutation component for chronic diseases.*** As mentioned earlier, multifactorial diseases have a high population frequency, but, unlike in the case of Mendelian diseases, the lack of adequate models to explain their stable frequencies in the population precluded any meaningful assessment of the radiation risk of these diseases. Descriptive models such as the multifactorial threshold model (MTM) of disease liability to explain the observed transmission patterns of these diseases and to estimate risks to relatives of affected individuals from data on population frequencies have existed for a long time but, as such, they are not suitable for assessing the impact of an increase in mutation rate on disease frequency. Similarly, although there was a wealth of literature on mechanistic models (that invoke mutation and selection as opposing forces in the evolution and maintenance of variability of polygenic/quantitative traits in populations), none of these models was geared towards assessing the impact of an increase in mutation rate on the frequency of multifactorial diseases.

(A 223) The ICRP Task Group drafting *Publication 83* (ICRP 1999b) took the first step in addressing the above issue by formulating a 'hybrid model' which included some elements of the MTM and some of the mechanistic models mentioned above. The hybrid model is henceforth referred to as the 'finite locus threshold model' (FLTM). Although the original intention was to use the model to estimate MC for both congenital abnormalities and chronic diseases, it soon became clear that its use for congenital abnormalities is not biologically meaningful and consequently, the 1999 Task Group decided to limit its use to chronic diseases only. As discussed

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later in this Annex, this does not pose any problem for estimating the risk of congenital abnormalities since this can now be done without recourse to the DD method. To provide a background, the assumptions and use of the MTM are first discussed below.

(A 224) ***Multifactorial threshold model (MTM) of disease liability.*** In the absence of information on the genetic or environmental factors that underlie multifactorial diseases, in the early 1960s the MTM used in quantitative genetics for threshold characters was extended to these diseases to explain their transmission patterns and estimate risks to relatives. Since multifactorial diseases are 'all-or-none' traits (unlike quantitative traits such as height or weight), in order to use the MTM for these diseases, it was necessary to postulate a hypothetical variable called 'liability' that underlies multifactorial diseases and a 'threshold' of liability which, when exceeded, would result in disease (Carter, 1961, Falconer, 1965). Worthy of note here is the fact that the MTM has been (and remains) useful for our understanding of familial aggregations and recurrence risks in families, and makes good predictions even when there is uncertainty about the underlying mechanisms. Details of the MTM for disease liability have been discussed in a number of publications (see ICRP, 1999b for a listing of the references).

(A 225) Briefly, the assumptions of the standard version of MTM are the following:

- all environmental and genetic causes can be combined into a single continuous variable called 'liability' which cannot, as such, be measured;
- liability is determined by a combination of numerous (essentially an infinite number of) genetic and environmental factors, that act additively, without dominance or epistasis, each contributing a small amount of liability and therefore show a Gaussian (normal) distribution; and
- the affected individuals are those whose liability exceeds a certain threshold value.

(A 226) The MTM enables the conversion of information on the incidence of a given multifactorial disease in the population (P) and in the relatives of those affected (q) into an estimate of correlation in liability between relatives from which a quantity called heritability (h^2), which provides a measure of the relative importance of genetic factors in disease causation, can be estimated.

(A 227) ***Heritability.*** Heritability, a common statistic used in quantitative genetics, provides a measure of the relative importance of transmissible genetic variation to the overall phenotypic variation. Since the phenotype owes its origin to genetic and environmental factors, in the analysis of variance, the total phenotypic variance (V_P) is usually partitioned into two components, genetic (V_G) and environmental (V_E), assuming that these are independent of each other (i.e., they are not correlated). The ratio V_G/V_P is called the 'broad-sense heritability', or degree of genetic determination, symbolised by h^2 (strictly, h^2_B). Estimates of the heritability of liability for many multifactorial diseases have been published in the literature and are in the range from about 0.30 to 0.80 although for most types of cancer the heritability coefficient is judged to be less than 0.30.

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(A 228) The genotypic variance, V_G, can be subdivided into an additive component (V_A) and a component due to deviations from additivity. Additive genetic variance is the component that is attributable to the average effects of genes considered singly, as transmitted in the gametes. The ratio, V_A/V_G, called 'narrow-sense heritability' h^2_N, determines the magnitude of correlation between relatives (Falconer, 1960).

(A 229) ***The finite-locus-threshold model used for estimating MC for chronic diseases.*** The FLTM incorporates the assumptions of liability threshold from the MTM (but suitably redefined to take into account mutations at a finite number of genes) and the concepts of mutation and selection from models on the maintenance and evolution of polygenic variability underlying quantitative traits. The choice of the FLTM was dictated by two main considerations: a) current knowledge of the genetic basis of well-studied chronic diseases, such as coronary heart disease (CHD), supports the view that a large proportion of the variability of intermediate quantitative traits (such as serum cholesterol levels, a risk factor for CHD) in the population is due to mutations at a limited number of gene loci (ICRP, 1999b, Sankaranarayanan et al., 1999) and b) in the absence of precise information on the genetic basis of most multifactorial diseases, the FLTM provides a useful starting point because, with such a model, the meaning of parameters reflecting mutation rates and selection can be quantitatively assessed in terms of those for single gene effects.

(A 230) Briefly, the FLTM assumes that the liability to disease, made up of genetic and environmental factors, is a continuous variable. The genetic component of liability is discrete, i.e., it is determined by the total number of mutant genes (defined as a random variable, g, the number of mutant genes in a genotype at n loci) and the environmental effect, e, which is a random variable which has a Gaussian (normal) distribution with mean = 0 and variance = V_e. The total liability therefore has two components: a) a function [$f(g)$] of the number of mutant genes in the n-locus genotype of an individual and b) a normally distributed environmental effect, e. The threshold characteristic of the model is described by assuming that individuals with liability exceeding a threshold value T are phenotypically affected and have a fitness of $(1 - s)$ and those below it are normal with fitness equal to 1.

(A 231) Although the mathematical formulations of the FLTM cannot be expressed in the form of a single equation, the predictions of the model can be iteratively evaluated from the computer program that was developed for this purpose. The steps include the following: first, with a defined set of parameter values (mutation rate, selection coefficients, threshold, etc.), the program is run until the population reaches equilibrium between mutation and selection. When this is achieved, the mutation rate is increased once or permanently and the computer run is resumed with the new mutation rate (with the other parameters remaining the same). The changes in the magnitude of MC and its relationship to heritability of liability (h^2) are examined in desired generations and at the new equilibrium. The h^2 estimates are not inputs, but outputs of the program, obtained with different combinations of parameter values (for the numbers of gene loci from 3 to 6, mutation rate, selection coefficients, environmental variance, and threshold). The conclusions discussed

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below are for the 5-locus model, but they remain qualitatively unaltered for other values of the number of gene loci.

(A 232) ***Main conclusions of the computer simulation studies.*** In these studies, a 5-locus model was used and the relationship between h^2 and changes in MC were assessed for two scenarios: a) the population sustains an increase in mutation rate every generation, and b) the population sustains an increase in mutation rate in one generation only. The initial (spontaneous) mutation rate assumed in the calculations was 10^{-6} per gene and the effects were examined for a 15% increase in mutation rate (i.e., 1.0 10^{-6}/gene to 1.15 10^{-6}/gene) with selection coefficients, $s = 0.2$ to 0.8. The conclusions are the following:

- Under conditions of a permanent increase in mutation rate, the MC at the new equilibrium is close to 1 over a wide range of h^2 values from about 0.3 to 0.8 that are of importance in the present context; stated differently, an x% increase in mutation rate will cause an x% increase in disease frequency at the new equilibrium.
- Again, under the same conditions and over the same range of h^2 values, the MC in the first several generations is very small, in the range 0.01–0.02, often closer to 0.01 than to 0.02. In other words, the predicted relative increase in disease frequency is very small.
- If the population sustains radiation exposure in one generation only, the MC in the first generation is as indicated in the previous conclusion, and its value gradually decays back to zero.
- The above three conclusions are valid when there is no sporadic component of disease, i.e., non-occurrence of individuals with disease that is unrelated to the genotype; when sporadics occur, the effect is to reduce the MC both in early generations and at the new equilibrium.

(A 233) The conclusions discussed above hold for so many different combinations of parameter values (i.e., threshold, selection coefficient, number of loci, environmental variance, spontaneous mutation rate, increases in mutation rate, etc.) that they can be considered robust. Additionally, it was found that, for mutation rates of the order known for Mendelian genes, the FLTM with a few loci and weak selection provides a good approximation to study the possible increases in the frequencies of chronic diseases in populations exposed to radiation.

(A 234) In its 2001 report UNSCEAR used MC = 0.02 as the best estimate in the risk equation for estimating the risk of chronic diseases.

The concept of potential recoverability correction factor

(A 235) The use of Eqn. (A.6.1) (i.e., risk = P × [1/DD] × MC) for risk estimation implies that the genes at which spontaneous mutations are known to cause disease (included under P) will also respond to induced mutations, that such mutations will be compatible with viability and therefore recoverable in live born progeny of irradiated individuals. This assumption gained support from studies of induced mutations in specific genes in several model systems. However, no radiation-induced

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germ-cell gene mutations, let alone induced genetic diseases, have thus far been identified in human studies.

(A 236) Advances in human molecular biology and in radiobiology have now shown that: a) spontaneous disease-causing mutations and radiation-induced mutations in experimental systems differ in several respects, both in their nature and in the mechanisms by which they arise (or are induced); b) there are both structural and functional constraints that preclude the recoverability of induced mutations in all genomic regions, i.e., only a small proportion of human genes of relevance from the disease point of view are likely to be responsive to radiation-induced mutations that are recoverable in live born progeny; and c) genes that have hitherto been used in studies on induced mutations are those that are non-essential for viability and also happen to be located in genomic regions, also non-essential for viability (reviewed in Sankaranarayanan 1999). So the crux of the argument is that the induced mutation rates from mouse studies that are used in risk estimation are likely to be overestimates of the rate at which induced mutations in humans will precipitate disease.

(A 237) Since there is no alternative to the use of mouse data on induced mutations for risk estimation, methods need to be devised to bridge the gap between empirically determined rates of induced mutations in mice and the rates at which disease-causing mutations may be recovered in human live births. One such method that has been developed involves the incorporation of a correction factor termed 'potential recoverability correction factor' (PRCF) into risk Eqn. (A.6.1) so that the risk now becomes a product of four quantities instead of the original three:

$$\text{Risk per unit dose} = \text{P} \times [1/\text{DD}] \times \text{MC} \times \text{PRCF} \qquad \text{(A.6.5)}$$

where the first three are as defined earlier and PRCF is the disease-class specific potential recoverability correction factor. Since PRCF is a fraction, the estimate of risk will now be lower.

(A 238) In order to estimate *potential recoverability* of induced mutations, a set of criteria was first defined using molecular information on recovered mutations in experimental systems. The operative words are the italicised ones, since a) knowledge of the structural and functional genomics of the human genome is not yet complete; b) so far, no radiation-induced human germ cell mutations have been recovered to provide a frame of reference; and c) the criteria may change with advances in knowledge in the coming years. The criteria that could be developed were then applied to human genes of relevance from the disease point of view, taking into account gene size, organisation, function, genomic context (i.e., whether the gene is located in a 'gene-rich' or 'gene-poor' region), spectra of spontaneous mutations in the gene, whether deletions, including contiguous genes, are known in the region, and the known mutational mechanisms. The question asked was: if a deletion (the predominant type of radiation-induced change) were to be induced in this gene/gene region, would it be potentially recoverable in a live birth?

(A 239) Details of the criteria used and the classification of the genes into three groups, viz. group 1, 'induced deletion is unlikely to be recovered', group 2, 'uncertain recoverability', and group 3, 'potentially recoverable', are discussed in detail by Sankaranarayanan and Chakraborty (2000b) and in the UNSCEAR (2001) report.

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Table A.6.2. Summary of assessments of potential recoverability of radiation-induced mutations in autosomal and X-linked genes.

Groups	No. of genes	Unweighted[a] PRCF	Incidence ($\times 10^4$)[b]	Weighted[c] PRCF
Autosomal dominants				
1 (unlikely to be recovered)	42	–	46.45	–
2 & 3 (uncertain + potentially recoverable)	17	0.29	55.90	0.157
Subtotal	59		102.35	
Autosomal dominants + X-linked				
1 (unlikely to be recovered)	43	–	48.95	–
2 & 3 (uncertain + potentially recoverable)	24	0.36	60.90	0.199
Total	67		109.85	

[a] Unweighted PRCF: aut. dominants: 17/59 = 0.29; aut. dominants + X-linked = 24/67 = 0.36.

[b] Estimates from Sankaranarayanan (1998) and Sankaranarayanan and Chakraborty (2000b).

[c] Weighted PCRF: aut. dominants: $(55.9 \times 17)/(102.35 \times 59) = 0.157$; aut. dominants + X-linked: $(60.9 \times 24)/(109.85 \times 67) = 0.199$.

Since the assignment to group 1 is less subjective (and therefore relatively more reliable), to err on the side of caution, potential recoverability was calculated as follows: if a total of N genes are analysed and if n among them could be excluded as 'unlikely to be recovered', the remainder (made up of groups 2 and 3) constitute $(N - n)$ and the fraction $(N - n)/N$ provides a crude measure of genes at which induced mutations may be recoverable. This fraction is called the 'unweighted' PRCF.

(A 240) The PRCF as estimated above, however, does not take into account differences in incidence of the different diseases. For example, if a disease with high incidence belongs to group 1, societal concern will be far less than when it belongs to the other groups. Consequently, a weighted PRCF was also calculated. If P is the total incidence of diseases due to mutations in N genes, and p is the incidence of diseases due to mutations in $(N - n)$ genes, then $[p(N - n)/PN]$ represents the 'weighted PRCF'.

(A 241) The results of analysis of a total of 67 autosomal and X-linked genes are summarised in Table A.6.2.

(A 242) ***PRCF for autosomal dominant and X-linked diseases.*** In view of the fact that autosomal dominants have an order-of-magnitude higher overall incidence than X-linked ones (1.5% versus 0.15%), the PRCFs for the former are more relevant. UNSCEAR therefore suggested the use of the PRCF range of 0.15 to 0.30 in the risk equation for estimating the risk of both autosomal dominant and X-linked diseases.

(A 243) ***PRCF for autosomal recessives.*** While the recoverability of induced recessive mutations is also subject to structural and functional constraints, in view of the fact that these mutations are first present in heterozygotes (and 50% of the gene products are generally sufficient for normal function), one can assume that even large deletions may be recoverable in the heterozygotes. Additionally, as discussed earlier, induced recessive mutations do not, at least in the first several generations, result in recessive diseases. Consequently, no attempt was made to estimate PRCF for

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recessive diseases. However, it should be noted that ignoring PRCF in the risk equation is equivalent to assuming PRCF = 1, but in reality this does not affect the estimate of risk – since MC is nearly zero in the first several generations, the product of P and MC is already zero.

(A 244) ***PRCF for chronic diseases.*** As may be recalled, in the FLTM used to estimate MC for chronic diseases, one of the assumptions is that of simultaneous increase in mutation rate in all the underlying genes which, in turn, causes the liability to exceed the threshold. A crude approximation of the PRCF for each multifactorial phenotype is the xth power of that for mutations at a single locus, where x is the number of gene loci, assumed to be independent of each other, that underlie the disease. Since the PRCF for single gene mutations is in the range from 0.15 to 0.30, for chronic diseases, the figures become 0.15^x to 0.30^x. With the assumption of just two loci, the estimates become 0.02 to 0.09 and, with more loci, substantially smaller. Intuitively, these conclusions are not unexpected when one considers that here one is estimating the probability of simultaneous recoverability of induced mutations at more than one independent gene.

(A 245) UNSCEAR adopted the PRCF range of 0.02 to 0.09 with the view that the use of this range will not underestimate risk.

(A 246) ***PRCF for congenital abnormalities.*** The available data do not permit PRCF estimation for congenital abnormalities. However, since risk estimation for this class of diseases is now done without using the DD method (see the next section), our inability to estimate PRCF is not a problem.

The concept that multisystem developmental abnormalities are likely to be the major manifestations of radiation-induced genetic damage in humans

(A 247) As discussed in the preceding paragraphs, in genetic risk estimation, the emphasis has been on expressing risks in terms of inducible genetic diseases, the expectation being that their phenotypes will be similar to those known from studies of naturally occurring genetic diseases. However, when one considers the following facts it is clear that the emphasis on genetic diseases gives only a partial answer to the question of genetic risks. The facts and observations are:

- radiation induces genetic damage through random deposition of energy;
- the whole genome is the target;
- most radiation-induced mutations studied in experimental systems are DNA deletions, often encompassing more than one gene;
- the recoverability of induced deletions is subject to structural and functional constraints so that only a small proportion of them are compatible with live births; and
- the phenotype of viability-compatible deletions will reflect the gene functions that are lost because of the deletion and we do not as yet have 'windows' for all genomic regions.

It follows therefore, that the problem in genetic risk estimation is one of delineating the phenotypes of viability-compatible deletions that may be induced in different genomic regions which may or may not have counterparts in naturally occurring genetic diseases.

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(A 248) ***Microdeletion syndromes in humans.*** Some inferences are now possible on the potential phenotypes of radiation-induced deletions from studies of naturally occurring microdeletion syndromes in humans. These result from deletions of multiple, physically contiguous, often functionally unrelated, genes that are compatible with viability in heterozygous condition and are identified clinically through a characteristic association of unusual appearance and defective organ development. Many examples of microdeletions have been (and continue to be) reported in the human genetics literature. They have been found in nearly all the chromosomes, but their occurrence in different chromosomal regions is non-random (e.g., Brewer et al., 1998). This is not unexpected in the light of differences in gene density in different chromosomes/chromosomal regions. The important point here is that, despite their occurrence in different chromosomes, the common denominators of the phenotype of many of these deletions are: mental retardation, a specific pattern of dysmorphic features, serious malformations, and growth retardation. These findings in humans are supported, among others, by studies of Cattanach et al. (1993, 1996) showing that, in the mouse, radiation-induced multilocus deletions constitute the genetic basis for a significant proportion of growth-retarded animals recovered in their work.

(A 249) It was therefore suggested that the predominant adverse effects of gonadal irradiation in humans are likely to be manifest as multisystem developmental abnormalities which are formally called 'congenital abnormalities' (Sankaranarayanan, 1999). However, unlike naturally occurring congenital abnormalities which are interpreted as being multifactorial, radiation-induced congenital abnormalities, because

Table A.6.3. Current estimates of genetic risks from continuing exposure to low-LET, low-dose or chronic irradiation (UNSCEAR, 2001) with assumed doubling dose of 1 Gy.

Disease class	Baseline frequency (per million live births)	Risk per Gy per million progeny:	
		1st generation	2nd generation
Mendelian			
Autosomal dominant & X-linked	16,500	~750 to 1500[a]	~1300 to 2500
Autosomal recessive	7500	0	0
Chromosomal	4000	[b]	[b]
Multifactorial			
Chronic	650,000[c]	~250 to 1,200	~250 to 1,200
Congenital abnormalities	60,000	~ 2,000[d]	~ 2400 to 3000[e]
Total	738,000	~3000 to 4700	~3950 to 6700
Total per Gy expressed as per cent of baseline		~0.41 to 0.64	~0.53 to 0.91

[a] The ranges reflect biological and not statistical uncertainties.

[b] Assumed to be subsumed in part under autosomal dominant and X-linked diseases and in part under congenital abnormalities.

[c] Frequency in the population.

[d] Estimated from mouse data without using the DD method.

[e] Newly induced damage of pre-existing damage (It is assumed that 20–50% of the progeny affected in the first generation will transmit the damage to the next generation resulting in 400 to 1000 cases.)

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they are multilocus deletions, are predicted to show, by and large, autosomal dominant patterns of inheritance. This prediction has been fulfilled in mouse radiation studies on skeletal abnormalities (Ehling, 1965, 1966, Selby and Selby, 1977), cataracts (Favor, 1989), growth retardation (Searle and Beechey, 1986), and congenital anomalies (Kirk and Lyon, 1984, Lyon and Renshaw, 1988, Nomura, 1982, 1988, 1994). No transmission tests could be carried out, however, for congenital abnormalities because they were ascertained in utero.

(A 250) ***Risk of developmental abnormalities.*** UNSCEAR (2001) used the mouse data on skeletal abnormalities, cataracts and congenital abnormalities (appropriately adjusting the rates for chronic low-LET radiation conditions) to obtain an overall estimate of the risk of developmental abnormalities about 20 10^{-4} Gy^{-1} (given in Table A.6.3 in this document under the heading 'congenital abnormalities' as 2000 per Gy per million for the first generation). All the data used in these calculations come from studies of irradiation of males, and the rate so estimated was assumed to be applicable to both sexes.

A.6.4. The 2001 UNSCEAR risk estimates

Estimates of genetic risk for a population sustaining radiation exposure generation after generation

(A 251) Table A.6.3 summarises the risk estimates presented in the 2001 UNSCEAR report. The risks given below and in the tables are expressed as the predicted number of additional cases (i.e., over the baseline) of different classes of genetic disease per million live births per Gy for a population exposed to low-LET, low-dose or chronic irradiation, generation after generation. For all classes except congenital abnormalities, the estimates are based on a DD of 1 Gy and the respective values of P, MC and PRCF for the different classes. For congenital abnormalities, the risk estimate comes from mouse data (discussed in the preceding paragraph) and is not based on the DD method.

(A 252) As can be noted from Table A.6.3, the first generation risk (i.e., the risk to the children of an exposed population) is estimated to be of the order of 750 to 1500 cases per million live births per Gy for autosomal dominant and X-linked diseases, zero for autosomal recessive diseases, 250 to 1200 cases for chronic diseases and 2000 cases of congenital abnormalities. The total risk is of the order of about 3000 to 4700 cases which represent about 0.4 to 0.6% of the baseline risk.

(A 253) The risk to the second generation (i.e., to the grandchildren) becomes slightly higher for all classes except for chronic diseases in view of the fact that the mutation component for these diseases does not increase over the first several generations.

Estimates of genetic risks for a population that sustains radiation exposure in one generation only

(A 254) The estimates of genetic risk under conditions when the population sustains radiation exposure in one generation only (and no further radiation in subsequent generations) are presented in Table A.6.4. Again, all estimates are expressed

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Table A.6.4. Current estimates of genetic risks from one-generation exposure to low-LET, low-dose or chronic irradiation (UNSCEAR, 2001) with assumed doubling dose of 1 Gy.

Disease class	Baseline frequency (per million live births)	Risk per Gy per million progeny:	
		1st generation	2nd generation
Mendelian			
Autosomal dominant & X-linked	16,500	~750 to 1,500[a]	~500 to 1,000
Autosomal recessive	7,500	0	0
Chromosomal	4,000	[b]	[b]
Multifactorial			
Chronic	650,000[c]	~250 to 1,200	~250 to 1,200
Congenital abnormalities	60,000	~ 2,000[d]	~ 400 to 1,000[e]
Total	738,000	~3,000 to 4,700	~1,150 to 3,200
Total per Gy expressed as per cent of baseline		~0.41 to 0.64	~0.16 to 0.43

[a] Risk to second generation is lower than that in the first because of the assumption that the radiation exposure occurs in one generation only; the risk will progressively decrease with time (in generations).

[b] Assumed to be subsumed in part under the risk of autosomal dominant and X-linked diseases and in part under that of congenital abnormalities.

[c] Frequency in the population.

[d] Estimate obtained using mouse data on developmental abnormalities and not with the doubling dose method.

[e] Under the assumption that about 20 to 50% of those affected in the first generation transmit the damage to the next generation.

per Gy per million progeny. As expected, the first generation risks (i.e., risks to the children of those exposed) are the same as those given in Table A.6.3. With no further radiation, the risk of autosomal dominant and X-linked diseases to the second generation (i.e., to the grandchildren) declines as a result of selection. For chronic multifactorial diseases, since the mutation component remains low for several generations, the risk to the second generation remains about the same as that in the first generation. The risk of congenital abnormalities is predicted to be of the order of 400 to 1000 cases (under the assumption that about 20 to 50% of those affected in the first generation transmit the damage to the next generation).

Strengths and limitations of the risk estimates

(A 255) On the basis of UNSCEAR (2001) the Commission has, for the first time, been able to provide ICRP estimates of risks for all classes of genetic diseases. While these estimates reflect the current state of knowledge in this area, the strengths and limitations of these estimates need to be borne in mind, in view of various assumptions that have been used.

(A 256) ***Equal mutational sensitivity of human males and females.*** The prevalent view that the mouse immature oocytes may not be an adequate model for assessing the mutational radiosensitivity of human immature oocytes necessitated the assumption that human females and males have the same mutational radiosensitivity which in turn is equal to that of mouse males. If, however, human females have a lower

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sensitivity in this regard, the average rate of induced mutations would be expected to be lower than the one used. In turn, this implies that the DD will be higher (and 1/DD will be smaller than 0.01 that has been used). At present it is not possible to address this issue.

(A 257) ***Average spontaneous and induced mutation rates used in DD calculations.*** As may be recalled, the average estimate of 2.95 10^{-6} per human gene was based on an estimated 135 genes underlying some 26 autosomal dominant disease phenotypes which constitute a subset of such diseases included in the estimate of baseline frequencies. Bearing in mind the fact that the human genome contains about 30,000 genes, one can only speculate whether the above average spontaneous mutation rate estimate is an over- or underestimate of the true average rate.

(A 258) Similarly, although the estimate of induced mutation rate for mouse genes is based on more data than was the case until now, the total number of genes included in the present analysis is still only 34 and, in a sizeable proportion of them, induced mutations were rare. Therefore, while the possibility remains that the presently estimated induced rate may be biased upwards, its extent is difficult to determine at present.

(A 259) ***Mutation components.*** The estimate MC = 0.3 for autosomal dominant and X-linked diseases is based on the average s value for the autosomal dominant diseases (since MC = s in the first generation), the data of which provided the basis for spontaneous mutation rate calculations. However, it should be realised that, for a substantial proportion of diseases, onset is in middle and later ages (i.e., beyond the age of reproduction) which means that s is smaller and therefore the MC value used may be an overestimate.

(A 260) ***Potential recoverability correction factors.*** For autosomal dominant and X-linked diseases, a range of PRCF from 0.15 to 0.30 was used, the lower limit being a weighted estimate and the upper limit, an unweighted one. However, the criteria developed for potential recoverability of induced deletions do not include breakpoint specificities which are undoubtedly important in the case of deletion-associated naturally occurring Mendelian diseases. It seems unlikely that radiation-induced deletions would share these specificities, and certainly not in all genomic regions. If these specificities are indeed relevant for recovering induced deletions, even the weighted PRCF may be an overestimate.

(A 261) For chronic diseases, it has been assumed that the PRCF may simply be the xth power of that for a single-gene disease, with x = the number of genes which have to be simultaneously mutated to cause disease; the values of 0.02 to 0.09 have assumed $x = 2$ (the minimum number). Although, statistically, such a calculation can be defended, the implicit biological assumption that, at low doses of radiation, two independent mutations underlying a chronic disease may be simultaneously induced and recovered seems unrealistic.

(A 262) There is an additional issue here, namely that the PRCF for chronic diseases is very sensitive to x (e.g., even if $x = 3$, the PRCF range becomes 0.003 to 0.03). The essence of the argument then is that the PRCFs used for chronic diseases may overestimate the risk.

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(A 263) ***Overlap in estimates of risk.*** It should be recalled that: a) the estimates for autosomal dominant and X-linked diseases have been obtained using the DD method; b) the risk of induced congenital abnormalities which are also adverse dominant effects have been estimated independently using mouse data without recourse to the DD method; and c) the risk of 'chromosomal diseases' has been assumed to be subsumed under the risk of autosomal dominant and X-linked diseases. The important point here is that, since all these represent dominant effects (and mutations in many developmental genes are known to cause Mendelian diseases), there must be overlap between the classes of risk grouped under the headings of 'autosomal dominant + X-linked' and 'congenital abnormalities' although it is difficult to assess its magnitude. The consequence is that the sum may overestimate the actual risk of dominant effects.

A.6.5. Earlier and present assessments of risk estimates by ICRP for deriving risk coefficients for genetic effects

ICRP Publication 60

(A 264) In *Publication 60* (ICRP, 1991b), the commission used the genetic risk estimates then available (UNSCEAR, 1988, NRC, 1990) as a starting point for deriving risk coefficients for 'severe heritable effects'. It is important to mention here that in the commission's calculations then, while the DD assumed (1 Gy) was the same as that used now, the baseline frequency of Mendelian diseases was only about one-half of that currently used (1.25% then versus 2.4% now). Additionally, for multifactorial diseases as a whole (estimated baseline frequency of 71%; same as now), the Commission assumed that MC = 0.05 for all post-radiation generations (this assumption is incorrect in the light of current calculations; see paragraphs (A 216) to (A 234)) and also incorporated an additional arbitrary correction factor (called 'severity correction factor') of 1/3 to estimate the proportion of inducible multifactorial diseases that may be deemed 'severe' (no such correction is used in the present assessments).

(A 265) For a population exposed to low-dose-rate, low-LET irradiation, the risk coefficients estimated by ICRP (1991b) are summarised in Table A.6.5 (see also Table 3 of Sankaranarayanan 1991).

(A 266) The estimates for the 'reproductive population' apply when the radiation doses received by all individuals in the population are genetically significant. However, when the total population of all ages is considered, the genetically significant dose will be markedly lower than the total dose received over a lifetime. Genetic damage sustained by germ cells of individuals who are beyond the reproductive period, or who are not procreating for any reason, poses no genetic risks. On the assumption that the average life expectancy at birth is of the order of 75 years, the dose received by 30 years of age (i.e., the mean reproductive age) is 40% (i.e., 30/75 = 0.4) of the total dose. The risk coefficients for the total population, therefore, are estimated to be 40% of the above values.

(A 267) Although ICRP (1991b) presented risk coefficients for the first two generations as well as for the new equilibrium, it used the equilibrium estimate of 1.0 10^{-2} Gy^{-1} for the total population (with an additional weighting factor for years of life

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Table A.6.5. Estimates of risk coefficients in *Publication 60* for a population sustaining continuous radiation exposure, generation after generation (ICRP, 1991b, Sankaranarayanan, 1991).

Time span	Disease category	Risk coefficient in % per Gy for	
		Reproductive population	Total population
Up to two generations	Mendelian & chromosomal	0.3	0.1
	Multifactorial	0.23	0.09
	Total	0.53	0.19
New equilibrium	Mendelian & chromosomal	1.2	0.5
	Multifactorial	1.2	0.5
	Total	2.4	1.0[a]

[a] The estimate used by ICRP (1991b) in its summary of 'nominal probability coefficients for stochastic effects' (Table 3, ICRP, 1991b); the figure given in that Table of 1.3 10^{-2} Gy^{-1} takes into account a weighting factor for years of life lost (ICRP, 1991b).

lost to arrive at a figure of 1.3 10^{-2} Gy^{-1} for 'severe heritable effects' in its summary table of 'nominal probability coefficients' (Table 3, ICRP 1991b).

Current assessments

(A 268) In its current assessments, the Commission used the estimates of risk presented in Table A.6.3 as starting points. The upper and lower limits of each of the estimated ranges were first used to obtain average estimates, and the latter were then combined to generate a single estimate of risk coefficient for all genetic effects. Details of calculations are given in the next section.

(A 269) ***Risk coefficients up to two generations for a population sustaining radiation exposure in every generation.***

- risk of Mendelian diseases = 1300 to 2500 cases per 10^6 progeny per Gy (= 0.13 10^{-2} to 0.25 10^{-2} Gy^{-1}; average: 0.19 10^{-2} Gy^{-1});
- risk of chronic multifactorial diseases = 250 to 1200 cases per 10^6 progeny per Gy (= 0.03 10^{-2} Gy^{-1} to 0.12 10^{-2} Gy^{-1}; average: 0.08 10^{-2} Gy^{-1});
- risk of congenital abnormalities = 2400 to 3000 cases per 10^6 progeny per Gy (0.24 10^{-2} to 0.30 10^{-2} Gy^{-1}; average: 0.27 10^{-2} Gy^{-1}); and,
- risk of all classes (i.e., the above three risks combined) = 3950 to 6700 cases per 10^6 progeny per Gy or 0.40 10^{-2} to 0.67 10^{-2} Gy^{-1}; average: 0.54 10^{-2} Gy^{-1}.

The above estimates are for a reproductive population. For the total population, the estimates are multiplied by 0.4. All the estimates are summarised in Table A.6.6.

(A 270) It is evident that, despite different baseline frequencies for Mendelian diseases, MCs and differences in risk estimates for comparable classes of diseases, the present estimates for the reproductive (0.54) as well as for the total population (0.22) are remarkably similar to those arrived at in ICRP *Publication 60* (1991b); respectively, 0.53 and 0.19; see Table 5. It should be stressed that this similarity is a matter of pure coincidence!

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Table A.6.6. Risk coefficients for the reproductive and the total population obtained up to two generations when the population sustains radiation exposure generation after generation (all values expressed in percent per Gy).

Disease class	Reproductive population		Total population
	Range	Average[a]	Average[b]
(a) Mendelian diseases	0.13 to 0.25	0.19	0.08
(b) Chronic diseases	0.03 to 0.12	0.08	0.03
(c) Congenital abnormalities	0.24 to 0.30	0.27	0.11
Total for all classes		0.54	0.22

[a] Average of the limits of the indicated ranges.
[b] 40% of that for the reproductive population.

(A 271) As may be recalled, the ranges in the estimates of risk coefficients for Mendelian and chronic diseases are a reflection of the ranges of PRCFs (0.15 to 0.30 for autosomal dominant and X-linked diseases and 0.02 to 0.09 for chronic diseases). Arguments to suggest that the upper limits of these ranges may represent overestimates and that the actual values may be closer to the lower limits were presented in Section A.6.3. If this reasoning is accepted, then it is meaningful to use the lower limit of the ranges for the above two classes of diseases and the average of the range for congenital abnormalities. When this is done, the risk coefficients become smaller than those presented in Table A.6.6 as noted below:

- *Reproductive population:* Mendelian diseases, 0.13; chronic diseases, 0.03; congenital abnormalities, 0.27; Total: 0.43 10^{-2} Gy^{-1}
- *Total population:* Mendelian diseases, 0.05; chronic diseases, 0.01; congenital abnormalities, 0.11; Total: 0.17 10^{-2} Gy^{-1}

(A 272) ***Risk coefficients for the first post-radiation generation only.*** The risk coefficients for the first post-radiation generation are summarised in Table A.6.7. Again as expected, the values are smaller than those up to the first two generations.

(A 273) If, however, the lower limits of the ranges for Mendelian and chronic diseases are used, then the estimates are 0.30 10^{-2} Gy^{-1} for the reproductive population

Table A.6.7. Risk coefficients for the reproductive population and the total population for the first post-irradiation generation (all values are expressed as per cent per Gy).

Disease class	Reproductive population		Total population
	Range	Average[a]	Average[b]
(a) Mendelian diseases	0.075 to 0.150	0.11	0.05
(b) Chronic diseases	0.025 to 0.120	0.07	0.03
(c) Congenital abnormalities	–	0.20	0.08
Total for all classes		0.38	0.16

[a] Average of the limits of the indicated ranges.
[b] 40% of that for the reproductive population.

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(i.e., 0.075 + 0.025 + 0.20 = 0.30) and 0.12 10^{-2} Gy^{-1} for the total population (i.e., [0.075 × 0.4] + [0.025 × 0.4] + [0.20 × 0.4] = 0.12).

Justification for using risk estimates up to generation two versus for calculating risk coefficients

(A 274) There are some problems in comparing genetic risk coefficients with those for cancers. This is because of the fact that cancer risk coefficients quantify the probability of harmful effects of radiation to the exposed individuals themselves, and genetic risk coefficients quantify the probability of harmful effects to the descendants of those exposed resulting from the induction of germline mutations and their transmission over generations. Following consideration of the available data and the recent analyses of UNSCEAR (2001) and NAS/NRC (2006), the Commission position is to express genetic risks up to the second generation (Table A.6.6). As given below, there are important scientific arguments that favour this approach.

(A 275) The population genetic theory of equilibrium between mutation and selection that underlies the use of the doubling dose method and the available mathematical formulations permit, in principle, the prediction of genetic risks at the new equilibrium (under conditions of continuous radiation in every generation). As noted earlier, in the absence of informative analyses and in order not to underestimate genetic risks, *Publication 60* (ICRP, 1991b) used the equilibrium estimates as a basis for calculating risk coefficients for genetic effects. The current arguments against such an equilibrium calculation centre on the very unrealistic and untestable assumptions that a) the estimates of selection coefficients, mutation components, and the other quantities used in the risk equation, will remain valid for tens or hundreds of human generations; b) the population structure, demography and health care facilities will remain constant over many hundreds of years.

(A 276) In the view of the Commission these assumptions can no longer be sustained and therefore, for the practical purposes of radiological protection, the Commission recommends a genetic risk estimate based upon risks up to the second generation. UNSCEAR (2001) and NAS/NRC (2006) have made the same judgement on this matter.

(A 277) The concepts that a) radiation-induced genetic changes are predominantly deletions, often encompassing more than one gene, and that only a small proportion of such induced deletions is compatible with live births, and b) radiation-induced heritable effects in humans are more likely to be manifest as multisystem developmental abnormalities in the progeny rather than as diseases due to mutations in single genes, are particularly relevant to this issue. Because reproductive fitness of the affected progeny will be reduced, many radiation-induced genetic changes affecting development are expected to be strongly selected against at the first and second generations. It is judged therefore that expressing genetic risks up to the second generation will not lead to any substantial underestimate of the heritable effects of radiation.

(A 278) Nevertheless a degree of caution is used in the derivation of a tissue weighting factor for the gonads. In respect of whole populations, Table A.4.1a gives relative detriment values of 0.044 for heritable effects and 0.017 for ovarian cancer.

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The sum of these computed values, 0.061, is less than the judged tissue weighting factor of 0.08 (Table A.4.3).

(A 279) In addition, the Commission notes that because of the different ways used to calculate the risk of autosomal dominant plus X-linked disease (the DD method) and congenital abnormalities (directly from mouse data), there must be a considerable element of 'double counting' of risk. Therefore, the summing of these risk categories, as used conventionally by UNSCEAR and ICRP, must represent a significant overestimate of genetic risk overall.

(A 280) Finally the Commission has considered whether an estimate of genetic risks at say 5 or 10 generations might be more appropriate. This judgement can be informed by some of the model predictions provided by UNSCEAR (UNSCEAR 2001).

(A 281) With the parameters specified, the model used by UNSCEAR and by the Commission predicts that, for a permanent increase in mutation rate, the responsiveness of disease incidence (mutation component, MC) is most pronounced for autosomal dominant diseases, less so for X-linked diseases, and far less pronounced for autosomal recessives. In this respect, for autosomal dominants, disease frequency in the population at generations 5 and 10 is predicted to be less than a factor 1.5 greater than that at generation 2 (Fig. V, UNSCEAR, 2001).

(A 282) The position regarding the responsiveness of multifactorial diseases is illustrated in Fig. VII of UNSCEAR 2001 which gives the relationship between mutation component and heritability of liability. These relationships are not significantly different at generations 1, 5 and 10. Further to this, for the dose rate of interest the model predicts minimal responsiveness (MC_{TU}) of these disorders at generation 10 to a permanent increase in mutation rate.

(A 283) It is notable that the above modelling predictions are wholly consistent with several animal genetic studies (largely with mice) that provide no evidence of the accumulation of a mutational load following x-irradiation at each generation up to more than 30 generations (reviewed by Green 1968 and UNSCEAR 1972).

(A 284) Overall, the Commission concludes that expressing the heritable risks of radiation at generations 5 or 10 rather than 2 would not materially affect judgements on the risk coefficient.

(A 285) In conclusion, the Commission, whilst fully recognising uncertainties, agrees with the UNSCEAR 2001 judgement (paragraph 531) that 'the risk estimates presented for the first two generations adequately reflect the current state of knowledge in this evolving area'. ICRP will maintain surveillance on scientific developments in the area and, if judged to be appropriate, will revise its estimates of these heritable risks.

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A.7. Summary of principal conclusions and proposals

(A 286) Although additional work was required, many of the conclusions and proposals from the Task Group that drafted this Annex are based upon ICRP Committee 1 judgements developed over the past 10 years or so. Accordingly many sections of the Annex are themselves summaries of these pre-existing judgements. For this reason a simple tabular format (Table A.7.1) has been used to provide an overall summary of the principal conclusions that have now been adopted by the Commission. The inclusion in Table A.7.1 of identifiers for the relevant sections and tables for each topic serves to map the document and guide readers to the topic of interest. These sections often detail methodologies, uncertainties and caveats not fully reflected in Table A.7.1. Accordingly Table A.7.1 cannot be taken as being fully informative of Commission views and judgements.

(A 287) The Commission also wishes to emphasise an important issue discussed in Annex B (drafted by a Task Group of ICRP Committee 2) of these Recommendations. The conclusions and proposals summarised in Table A.7.1 are principally for the broad purposes of prospective planning in radiological protection. For other purposes many of the proposed judgements may well be insufficient, and in these circumstances, specific, well-justified judgements on radiation effects and their health risks will need to be made.

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Table A.7.1. Summary of principal conclusions and proposals specifically intended for radiological protection purposes.

	Topic	Data source/methodology	Conclusions/numerical judgements
1	Dose response at low doses/dose rates for cancer and heritable effects (*Sections A.2.1–A.2.5, A.2.7–A.2.8, A.4.1 paragraphs A89-A96*)	Judgements based on studies reviewed in *Publication 99* (ICRP, 2005d), UNSCEAR 2000, 2001, NCRP 2001, NAS/NRC 2006	Uncertainties are considerable but the balance of evidence weighs in favour of the use of a simple proportionate relationship between increments of dose and risk
2	Role of induced genomic instability, bystander signalling and adaptive responses in the risk of induced health effects (*Sections A.2.3, A.2.5, A.4.1 paragraphs A90-A97*)	Judgements based on studies reviewed in ICRP *Publication 99*, NCRP 2001, UNSCEAR 2000, UNSCEAR 1994, NAS/NRC 2006	Knowledge of these biological effects is growing but is currently insufficient for radiological protection purposes
3	Relative biological effectiveness and radiation weighting factors (w_R) (*Section A.4.3*)	Judgements based upon recommend-ations included in *Publication 92* (ICRP, 2003c)	Judgements are fully developed in Annex B
4	Dose and dose-rate effectiveness factor (DDREF) and the impact of a possible dose threshold (*Sections A.2.4, A.4.2, A.4.4 paragraphs A125-A148, A.4.4 paragraphs A173-A187*)	Judgements largely based upon studies reviewed in *Publication 99,* UNSCEAR 2000 and NAS/NRC 2006	A DDREF value of 2 should be retained for use by ICRP; the uncertain possibility of a low-dose threshold for cancer risk is equivalent to an uncertain increase in the value of DDREF.
5	Radiation detriment and tissue weighting factors (w_T) (*Section A.4.4 paragraphs A105-A162*)	New judgements developed largely from cancer incidence in the A-bomb Life Span Study (LSS), international cancer mortality databases and new estimates of heritable effects (see 7 below); judgements supported by additional consideration of cancer mortality data	Revised w_T scheme proposed; significant w_T changes for breast and gonads (see Table A.4.3), revised method for treatment of remainder tissues (see Table A.4.3)
6	Detriment adjusted nominal risk coefficients for cancer (*Section A.4.4 paragraphs A105-A162*)	New risk estimates developed based upon lethality/life impairment weighted data on cancer incidence (see 5 above)	Detriment adjusted nominal risk coefficients of 5.5 10^{-2} Sv^{-1} for the whole population and 4.1 10^{-2} Sv^{-1} for adult workers are proposed (see Table A.4.4.)

7	Detriment adjusted nominal risk coefficients for heritable effects (*Section A.6*)	New risk estimates based upon UNSCEAR 2001 judgements using risks for all classes of heritable effects up to the second post-irradiation generation (see Tables A.6.4 and A.6.6)	Second generation, detriment adjusted nominal risk coefficients of 0.2 10^{-2} Sv^{-1} for the whole population and 0.1 10^{-2} Sv^{-1} for adult workers are proposed (see Table A.4.4); *Publication 60* (ICRP, 1991b) used population genetic risks at a theoretical equilibrium so the present estimates are markedly lower
8	Cancer risk following in-utero exposures (*Section A.4.4 paragraphs A168-A171*)	Judgements based upon the studies reviewed in *Publication 90* (ICRP, 2003a)	Life-time cancer risk judged to be no greater than that following exposure in early childhood
9	Genetic susceptibility to radiation-induced cancer (*Sections 2.7 paragraphs A46-A48, A.4.4 paragraph 172*)	Judgements based upon studies reviewed and analyses made in *Publication 79* (ICRP 1998a), UNSCEAR 2000, 2001 and NAS/NRC 2006	Strongly expressing cancer-predisposing disorders are too rare to appreciably distort risk estimates for the whole population; the impact of potentially common but weak genetic determinants remains uncertain
10	Radiation-induced tissue reactions in adults (*Sections A.2.6 and A.3*)	Mechanisms have been re-evaluated and dose thresholds for morbidity/mortality revised on the basis of various data	Tables A.3.1, A.3.2, and A.3.4 provide revised judgements but with few changes from other ICRP publications. The dose threshold for cataract induction and judgements on dose limits for the eye require further attention.
11	In-utero risks of tissue reactions, malformations and neurological effects (*Section A.3.2*)	Judgements based upon studies reviewed in *Publication 90*	Strengthened judgement on the existence of a dose-threshold for tissue reactions, malformation and severe mental retardation – therefore, absence of risk at low doses. Greater uncertainty for IQ deficits but low-dose risk judged to have no practical significance
12	Risks of non-cancer diseases (Section A.5)	Judgements based upon LSS data and studies on post-radiotherapy outcomes particularly for cardiovascular disease	Great uncertainty on the form of the dose-response below 1 Sv – no specific judgement on low-dose risk is possible

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ANNEX B. QUANTITIES USED IN RADIOLOGICAL PROTECTION

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Preface to Annex B

When the Commission initiated its project to review and update its 1990 Recommendations, at the Main Commission meeting in Cape Town, South Africa, in 1998, it was clear from the outset that the main text of the new Recommendations would need to be supported by scientific Annexes and reports in much the same manner as the 1990 Recommendations.

Therefore, ICRP Committees 1 (on radiation effects) and 2 (on doses from radiation exposure) were asked to outline and begin to draft Annexes on the health effects of radiation and on dosimetric considerations. (Committees 3 on protection in medicine and 4 on application of ICRP recommendations were similarly asked to produce supporting documents which were and are being published as separate reports: *Publication 105*, ICRP (2007b) on protection in medicine and *Publication 101*, ICRP (2006a), on assessing dose to the representative person and on optimisation).

After initial plenary work, Committee 2 formed a Task Group in 2001 to advise the Main Commission and draft the present Annex to the Recommendations.

The membership of the Task Group was as follows:

C. Streffer, Chair	G. Dietze	K. Eckerman
J. Harrison	H. Menzel	J. Stather

The corresponding members were:

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J. Stather, Vice-Chair	Y. Zhou	

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Executive summary

(B a) Dosimetric quantities are needed to assess radiation exposures to humans and other organisms in a quantitative way. This is necessary in order to describe dose–response relationships for radiation effects which provide the basis for risk estimation in radiological protection.

(B b) Absorbed dose, D, is the basic physical quantity for radiological protection. It is defined as the mean of the distribution of energy deposited in a tissue volume. It is well defined at any point in matter. It is measurable. In the low dose range, important for radiological protection, the distribution of energy deposition is heterogeneous, particularly in the case of exposure to high-LET radiation. In practical applications, averaging of absorbed dose over organ or tissue volumes is performed. It is assumed that the mean value of absorbed dose in an organ or tissue is correlated with radiation detriment from stochastic effects in the low dose range. The averaging of absorbed doses in tissues and organs of the human body and their weighted sum are the basis for the definition of protection quantities. Dose distributions that are highly heterogeneous (e.g., DNA precursors labelled with tritium or Auger emitters) may need special treatment.

(B c) The definition of protection quantities is based on the mean absorbed dose, $D_{T,R}$, in an organ or tissue T, due to radiation of type R. The protection quantity equivalent dose, H_T, is defined by

$$H_T = \sum_R w_R D_{T,R}$$

where w_R is the radiation weighting factor for radiation R. These w_R values are based on experimental data for the relative biological effectiveness (RBE) of various types of radiations at low doses, on biophysical considerations and on judgements. A set of w_R values was given in *Publication 60* (ICRP, 1991b). The general concept of these values remains unchanged. Some modifications are recommended: The w_R value for protons is reduced to a factor of 2 and a continuous function is used for neutrons with a reduction of the w_R value to 2.5 at energies below 10 KeV and above 1 GeV. The principal definition of effective dose,

$$E = \sum_T w_T H_T$$

remains unchanged from *Publication 60* (ICRP, 1991b). However, some of the tissue weighting factors, w_T, have been changed on the basis of new epidemiological data for cancer induction (see Annex A).

(B d) The w_T values are age- and sex-averaged. Therefore E is not calculated for an individual but for a Reference Person. The Commission has now defined sex-specific computational phantoms for a Reference Male and a Reference Female. These phantom models will be used for calculations of dose conversion coefficients for external exposures and dose coefficients for internal exposures. The new sex-specific computational models allow the calculation of male and female organ doses separately, from which the averaged equivalent organ doses are calculated. These are

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used for the calculation of E. Computational phantoms for chinldren of various ages and the fetus will also be defined. With the assumption of the linear-non-threshold dose response for stochastic radiation effects (LNT model) in the low dose range (< 100 mSv) and, under the conditions of the described concept of calculation, E is an additive quantity. At higher radiation doses, when tissue reactions (deterministic effects) can occur, the absorbed doses in organs and tissues have to be used for risk evaluation. In the case of high-LET radiation exposures, appropriate RBE values relating to deterministic effects should be used.

(B e) The body related protection quantities (equivalent dose and effective dose) cannot be applied directly in radiation monitoring as they are not directly measurable. Operational quantities are measured instead for the assessment of E and H_T. For external exposures, operational dose equivalent quantities have been defined for area and individual monitoring. Measurements with an area monitor are preferably performed free in air, and personal dosimeters are worn on the body. The radiation fields 'seen' by these dosimeters differ and therefore different operational dose quantities have been defined. Dose equivalent quantities, based on doses to the depth of 10 mm and 0.07 mm of the ICRU sphere or in the human body respectively, have been recommended. E and organ doses are calculated by dose conversion coefficients for external exposure. For dose assessment from internal exposures, the intake of radionuclides and the resultant equivalent dose as well as the effective dose are calculated on the basis of direct (e.g., measuring radioactivity of the whole body) or indirect (e.g., measuring the radioactivity in excreta) measurement using biokinetic models describing the behaviour of the radionuclide in the body.

(B f) Dose quantities in radiological protection for workers and the general public are needed mainly for prospective dose assessment in planned exposure situations and optimisation as well as for retrospective dose assessments for testing compliance with dose limits. The intake of a radionuclide during a year is assigned a committed effective dose. A commitment period of 50 years is considered for adults, and to age 70 years for children. The annual effective doses of workers and of members of the public are the sum of the effective dose obtained within one year from external exposure and the committed effective dose from radionuclide intake during this year.

(B g) For external exposures at workplaces usually the effective dose is assigned by measuring personal dose equivalent, Hp(10), as an acceptable assessment, assuming uniform whole body exposure. The committed effective dose from intakes of radionuclides is assessed by considering the ingestion and inhalation of radioactive materials. Public exposures can occur from natural radiation sources and from technical installations. Doses are mainly determined by environmental measurements, habit data and modelling. The use of E for medical exposures of patients has important limitations, as often only parts of an organ or the human body are exposed, and the age distribution of patients differs from that of the general public; other factors may also need to be considered.

(B h) The primary use of E is for demonstrating compliance with dose limits. In that sense it serves to limit and to regulate the occurrence of stochastic effects in the low dose range, and it is used for regulatory purposes worldwide. E is calculated on the basis of reference values for a Reference Person. The weighting factors are

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selected from a range of experimental and epidemiological data by judgement, and they apply to a population of all ages and both sexes. For retrospective dose and especially risk assessments in individual cases individual parameters such as sex, age and organ doses would need to be taken into account. *E* should not be used for epidemiological studies. In the case of accidents that could give rise to deterministic effects it is necessary to estimate absorbed dose and dose rates to organs and tissues. Considerations of threshold doses are then important and, for exposures to high-LET radiation, appropriate RBE values have to be chosen.

(B i) Collective effective dose is retained as an important and useful instrument for optimisation especially for occupational exposures. In the past, collective effective dose was frequently computed as the sum of radiation exposures over a wide range of doses, over long time periods and over large geographical regions. On this basis radiation-related detriments have been calculated. Such calculations are not meaningful because large uncertainties are included with respect to the dose assessments and extrapolation procedures from high and medium radiation doses to very low doses. To avoid the aggregation of low individual doses over extended time periods, limiting conditions have to be set. The following aspects could be considered: number of exposed individuals, age and sex of exposed individuals, range of individual doses, dose distribution in time, and geographical distribution of exposed individuals.

(B j) For the dose assessments in radiological protection a number of models and parameter values are necessary. These have been developed from experimental investigations and human studies in order to derive 'best estimates' of model parameter values. It is recognised that in some cases there may be large uncertainties in these values. Besides these uncertainties, the biological variability is high for many parameters and therefore reference values have to be selected from a wide range of values. These reference values and models have been fixed by convention and thus are point values without uncertainty. They are periodically re-evaluated and may be updated when new scientific data become available. The reference systems are mainly developed for prospective dose assessments in regulatory processes. For dose assessments, and especially for risk estimates in dose ranges above the dose limits, and in individual cases, uncertainties in models and parameter values may need to be taken into consideration.

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B.1. Introduction

(B 1) For establishing principles and systems of radiological protection, dosimetric quantities are needed to assess the radiation exposures of humans and other organisms in a quantitative way. The quantification of radiation doses for exposed human populations or experimental animals is also important for developing dose–response relationships for radiation effects. Such relationships are used over wider dose ranges than those for which data are available, particularly in the low dose range, which is important for radiological protection.

(B 2) The development of health effects caused by ionising radiation starts with the physical processes of energy absorption in biological tissues, resulting in ionisations which cause molecular changes and which may occur in clusters, e.g., in the genetic information of cells, the DNA in the cell nucleus. This damage manifests itself as radiation damage to the organs and tissues of the body which can result in both short-term and long-term health effects. At high doses acute damage to organs and tissues mainly arises as a result of loss of function involving cell killing and, in extreme cases, can cause death of the exposed individual. These types of damage are termed *deterministic effects* (*Publication 60*, ICRP, 1991b) or *tissue reactions* (see Annex A, paragraph A 56), having previously been called *non-stochastic* effects in *Publication 26* (ICRP, 1977). At lower doses and at low dose rates these tissue reactions are not seen, but damage to the genetic material may occur that can result in an increase in the risk of cancer observed years later, or heritable disease in future generations. Such damage continues to be termed *stochastic* as the probability of the effect, but not its severity, is assumed to increase with dose.

(B 3) Other interactions with cells, organs and tissues may also be important in understanding the response of the body to radiation exposure (for example damage to membranes), as described in Annex A. However, it is concluded that the information on the implications of other responses in terms of the observed tissue effects is unclear at present, and that such effects cannot at present be taken into account in dose and risk assessments for protection purposes.

(B 4) Radiological protection is concerned with controlling exposures to ionising radiation so that tissue reactions are prevented and the risk of stochastic effects is limited to acceptable levels. For assessing doses from radiation exposures special *dosimetric quantities* have been developed by ICRP and by the International Commission on Radiation Units and Measurements (ICRU). The fundamental *protection quantities* adopted by ICRP are based on measures of the energy imparted to organs and tissues of the human body. These quantities allow quantification of the extent of exposure to ionising radiation from both whole and partial body irradiation from external radiation sources and from intakes of radionuclides. The estimated doses can then be compared with recommended dose limits for people who are occupationally exposed and for members of the public.

(B 5) This scheme of quantities was first adopted by the Commission in its Recommendations in *Publication 26* (ICRP, 1977). The quantities were modified in the 1990 Recommendations in *Publication 60* (ICRP, 1991b) and have been developed further in the 2007 Recommendations.

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(B 6) For demonstrating compliance with dose limits, it is useful to have a single protection quantity specifying the 'amount' of whole or partial body exposure which is quantitatively related to the probability of an effect for all types of radiations, regardless of whether the radiation is incident on the body or emitted by radionuclides within it. Achieving this ideal is complicated by variations in the response of organs and tissues to radiations of different quality and by the varying radiosensitivity of the organs and tissues of the body. These effects generally influence the radiation response of all members of the population in a similar way. Therefore they were taken into account in the protection quantities recommended in *Publication 26* using quality factors and tissue weighting factors and in *Publication 60* using radiation and tissue weighting factors. Individually related factors including sex, age and individual sensitivity will also influence the risk but such biological effects are not taken into account in the definition of the protection quantities, which are applied for all members of the population.

(B 7) In *Publication 26* the different qualities of ionising radiation were considered with the quantity dose equivalent. The dose equivalent, H, was defined by

$$H = DQN \tag{B.1.1}$$

where D is the absorbed dose at a point in the specified tissue and Q is the *quality factor* for the specific radiation at this point. N was included to cover any other factor that could modify the risk from a radiation dose. However, in *Publication 26* no such modifying factors were specified. Hence the definition of H was later changed to

$$H = DQ \tag{B.1.2}$$

(see ICRP, 1991b, ICRU, 1993b).

(B 8) The Commission first introduced the protection quantity, *effective dose equivalent*, in *Publication 26* (ICRP, 1977) as proposed by Jacobi (1975). It was intended to be used for exposure limitation and risk management at low doses and was developed principally for use in relation to occupational exposure, although it has also been used more broadly for members of the public. The Commission updated this concept in *Publication 60* (ICRP, 1991b) with the quantity *effective dose*. The underlying principle was to use the *absorbed dose* as the fundamental physical quantity, to average it over specified organs and tissues and then to apply suitably chosen weighting factors to take account of differences in biological effectiveness of different radiations and the differences in radiation sensitivities of organs and tissues to stochastic health effects.

(B 9) The development of effective dose equivalent and subsequently effective dose has made a very significant contribution to radiological protection as it has enabled doses to be summed from whole and partial body exposure from external radiation and from intakes of radionuclides.

(B 10) Effective dose, as defined in *Publication 60*, has been implemented into legislation and regulations in many countries worldwide. It has been shown to provide a practicable approach to the management and limitation of radiation risk in relation to both occupational exposures and exposures of the general public. The general acceptance of effective dose as well as the demonstration of its practicability are

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important reasons for maintaining it as the central quantity in radiological protection.

(B 11) Effective dose cannot be measured directly in the body. The protection system therefore includes *operational quantities* that can be measured (Fig. B.1) and used to assess effective dose. ICRU has developed a set of operational dose quantities for exposure to external radiation which were evaluated by a joint Task Group of ICRP and ICRU (*Publication 74*, ICRP, 1996b). The analysis in *Publication 74* indicated that the operational dose quantities recommended by ICRU generally achieve the objective of providing 'measurable quantities that adequately represent the protection quantities'. For internal exposures following intakes of radionuclides, activity quantities in combination with dose coefficients developed by ICRP are also used as operational quantities.

(B 12) There are a number of aspects to the dosimetry system given in *Publication 60* that needed to be addressed and further clarified. This Annex considers the dosimetric quantities developed by ICRP for radiological protection purposes and provides a detailed description of the Commission's dosimetry system adopted in these Recommendations. The health effects resulting from exposures to ionising radiation are briefly summarised in Section B.2, and their place in setting and applying protection standards are described. The basis for the development of the tissue weighting factors, w_T, is summarised although this is considered in more detail in Annex A. Section B.3 considers the development of the dosimetric quantities and those adopted in these Recommendations. It also examines tissue and radiation weighting factors in more detail, with emphasis on the latter. Section B.4 describes the

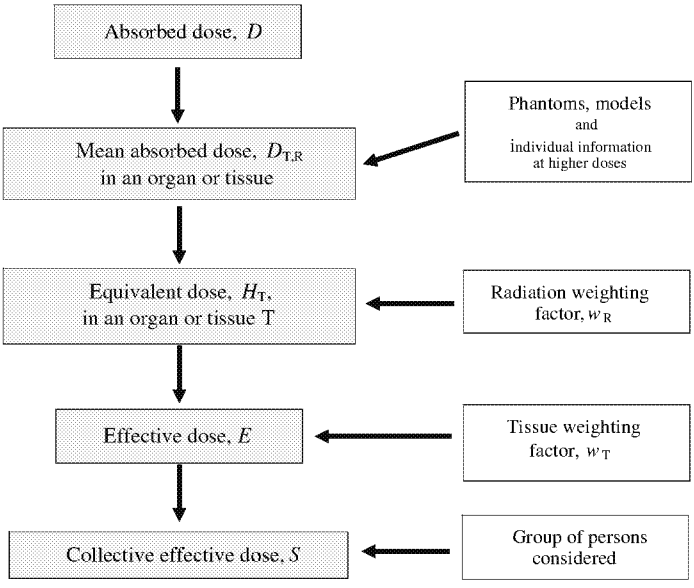

Fig. B.1. System of dose quantities for use in radiological protection.

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operational quantities developed in conjunction with ICRU. The practical application of these dosimetric quantities in radiological protection, together with a discussion of situations in which the use of effective dose is, or is not, appropriate is covered in Section B.5. Finally, Section B.6 examines uncertainties and judgements that may need to be considered in using these quantities.

B.1.1. References, Section B.1

ICRP, 1977. Recommendations of the International Commission on Radiological Protection. ICRP Publication 26. Ann. ICRP 1(3).

ICRP, 1991b. 1990 Recommendations of the ICRP. ICRP Publication 60. Ann. ICRP 21 (1–3).

ICRP, 1996b. Conversion coefficients for use in radiological protection against external radiation. ICRP Publication 74. Ann. ICRP 26 (3/4).

ICRU, 1993b. Quantities and units in radiation protection dosimetry. ICRU Report 51. ICRU Publications: Bethesda, MD.

Jacobi, W., 1975. The concept of effective dose – A proposal for the combination of organ doses. Radiat. Environ. Biophys. 12, 101–109.

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B.2. Health effects

(B 13) Radiological protection in the low dose range is primarily concerned with protection against radiation-induced cancer and heritable diseases. These diseases are termed stochastic effects, as they are probabilistic in nature. It is assumed that any exposure is capable of causing an effect, with no threshold (Annex A). As a consequence it is not possible to prevent stochastic risks and dose limits are set to limit their occurrence and thus to prevent unacceptable levels of risk. As indicated above, ICRP has developed the quantity effective dose to allow doses from external and internal exposure to be assessed on a common basis by using the above mentioned weighting factors.

(B 14) At exposures giving an absorbed dose above about 0.5–1 Gy (for low-LET radiation; LET: linear energy transfer, see Section B.3.5.1), associated mainly with accident situations, tissue reactions may occur if exposures exceed threshold doses for such health effects (Annex A). These thresholds vary with dose rate and with radiation quality, and the extent as well as the severity of the effect increases with increasing dose and dose rate. Tissue reactions must be considered separately from stochastic effects and cannot be addressed within the framework of effective dose and its parameters, w_R and w_T.

B.2.1. Stochastic effects

(B 15) Exposure to ionising radiation, even at low doses, may cause damage to the nuclear (genetic) material in cells that may result in the development of radiation-induced cancer many years later, heritable disease in future generations and some developmental effects under certain conditions (ICRP, 2003a). The induction of cancer by low-LET radiation has been firmly demonstrated in the dose range of about 100 mGy and higher, and it was concluded by UNSCEAR that 'studies on DNA repair and the cellular/molecular processes of radiation tumorigenesis provide no good reason to assume that there will be a low-dose threshold for the induction of tumours in general' (UNSCEAR, 2000). Radiation-induced heritable disease has not been demonstrated in human populations but there is substantial evidence from animal studies of heritable damage to germ cells (ova and spermatozoa as well as their precursor cells). For both radiation-induced cancer and heritable disease it is the probability of the occurrence of the effect, not its severity, that depends upon the dose. The general assumption for radiological protection is that the risk of these stochastic effects increases in the low dose range linearly with dose, with no threshold (LNT model) (UNSCEAR, 2000, Streffer et al., 2004, Annex A).

(B 16) Annex A gives detailed information on the risk of radiation-induced cancer in organs and tissues of the body and on dose–response relationships as well as of heritable disease. It is notable that there are significant differences in sensitivity to cancer induction among the organs and tissues of the body. Thus, for example, the thyroid in children, the female breast and the bone marrow have a relatively high sensitivity for the induction of solid cancer and leukaemia whereas the muscle and connective tissue have a relatively low sensitivity.

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(B 17) Annex A also gives information on other stochastic effects that may occur following radiation exposure. This includes damage to the vascular tissue of the circulatory system of blood. At present, however, insufficient data are available to determine any dose–response relationships in the dose range below about 0.5 to 1 Gy or to use them as a basis for setting dose limits.

(B 18) A central position of the Recommendations in *Publication 26* (ICRP, 1977) was that the overall risk of stochastic effects at exposures corresponding to the Commission's dose limits are approximately equal, regardless of the manner of irradiation – whether the body is uniformly or heterogeneously irradiated from external radiation or from intakes of radionuclides if the sensitivity to the different types of radiation are correctly considered. This principle resulted in the inclusion of two types of weighting factors in the definition of effective dose equivalent for use in radiological protection.

(B 19) The quality factors, first used in *Publication 6* (ICRP, 1964), allowed for the relative effectiveness of different radiations in causing biological effects and could be thought of as the factor representing the relative biological effectiveness (RBE) of the radiation. Experimental measurements of RBE in cellular studies in vitro, and in animal studies, show that high-LET radiations, including neutrons and alpha particles, cause more damage per unit of absorbed dose than low-LET radiations. The weighting factors, w_T (later termed tissue weighting factors in *Publication 60*) accounted for the varying radiation sensitivity of tissues to the induction of stochastic effects.

(B 20) The w_T values recommended by the Commission in *Publication 26* were based on the risk of fatal cancer and of serious heritable disease in the first two generations (Table B.1). *Publication 60* (ICRP, 1991b) developed this concept further with an extended set of tissue weighting factors based upon more information on stochastic radiation effects on tissues and a broader concept of radiation detriment. In addition to assessing the risk of radiation-induced fatal cancer and heritable disease in all future generations it also took into account the severity of the disease and the years of life lost in determining total radiation detriment. Radiation detriment then provided the basis for setting revised values of tissue weighting factors, w_T, in *Publication 60* (Table 1). In addition, radiation weighting factors, w_R, replaced quality factors, Q, in the definition of the protection quantities. The assumption was made that, for protection purposes, the weighting factors are independent of dose and dose rate in the low dose range. Values of w_R are taken to be independent of the organ or tissue irradiated and w_T values to be independent of the type and energy of radiation.

(B 21) In the 2007 Recommendations, the Commission has further developed the concept of tissue weighting factors, and now bases values of w_T to a large extent on the incidence of radiation-induced cancer rather than on mortality as well as on the risk of heritable disease over the first two generations (Annex A). This is considered to be a more appropriate basis for the assessment of radiation detriment. The risk of cancer is again adjusted for severity and for years of life lost. The tissue weighting factors given in the 2007 Recommendations are presented in Table B.2 and discussed further in Section B.3.5, paragraphs B 132 – B 145.

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Table B.1. ICRP Recommendations for tissue weighting factors in *Publication 26* (1977) and *Publication 60* (1991b).

Tissue	Tissue weighting factor, w_T	
	1977 *Publication 26*	1991 *Publication 60*[2,3]
Bone surfaces	0.03	0.01
Bladder		0.05
Breast	0.15	0.05
Colon		0.12
Gonads	0.25	0.20
Liver		0.05
Lungs	0.12	0.12
Oesophagus		0.05
Red bone marrow	0.12	0.12
Skin		0.01
Stomach		0.12
Thyroid	0.03	0.05
Remainder	0.30[1]	0.05
TOTAL	1.0	1.0

[1] The five most highly irradiated other organs and tissues are included in remainder, each with a $w_T = 0.06$.

[2] The values have been developed from a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effective dose they apply to workers, to the whole population, and to either sex.

[3] Further footnotes in *Publication 60*. Table 5.2, page 68.

Table B.2. Tissue weighting factors, w_T, in the 2007 Recommendations.

Organ/Tissue	Number of tissues	w_T	Total Contribution
Lung, stomach, colon, bone marrow, breast, remainder	6	0.12	0.72
Gonads	1	0.08	0.08
Thyroid, oesophagus, bladder, liver	4	0.04	0.16
Bone surface, skin, brain, salivary glands	4	0.01	0.04

1. The w_T for gonads is applied to the mean of the doses to testes and ovaries.
2. The dose to the colon is taken to be the mass-weighted mean of ULI and LLI doses, as in the *Publication 60* formulation.
The specified remainder tissues (14 in total, 13 in each sex) are: adrenals, extrathoracic tissue (ET), gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine (SI), spleen, thymus, uterus/cervix (♀).

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B.2.2. Tissue reactions (deterministic effects)

(B 22) At doses much higher than the dose limits recommended in the protection system, and especially in accident situations, radiation exposures may cause *deterministic effects* (tissue reactions). These effects result from the impairment of the integrity and function of organs and tissues: clinically observable damage then occurs above a threshold dose, although the extent of any damage depends upon the absorbed dose and dose rate as well as radiation quality. The expression of injury varies from one tissue or organ to another depending upon cellular radiosensitivity, the function of differentiated cells, cellular composition, and cell renewal capacity. Loss of reproductive capacity of cells, the development of fibrotic processes and cell death play a central role in the pathogenesis of most tissue reactions. Some of the most sensitive tissues, with respect to early tissue reactions, are those with rapidly proliferating cell systems including haematopoietic tissue, the cells lining the gastrointestinal tract, the basal cell layer in the skin, and the male germ cells. Late tissue reactions may also depend in part on damage to blood vessels or connective tissue elements that are essential for the functioning of all organs and tissues as well as of the lens of the eye. Such damage can be expressed many months or even years after radiation exposure.

(B 23) High-LET radiations, such as neutrons and alpha particles, cause more damage per unit of absorbed dose than low-LET radiation. Values of RBE for tissue reactions were given in *Publication 58* (ICRP, 1989b). In general the RBE values were found to be lower for tissue reactions than those for stochastic effects at low doses and to vary with the tissue damage described.

(B 24) The radiation weighting factors, w_R, for high-LET radiation are derived for stochastic effects at low doses. The application of these w_R values to assess the exposure and damage at high doses, when compared with photon irradiation, would result in an over-estimate of the occurrence and severity of any tissue reaction. When assessing radiation exposure for determining the potential for tissue reactions, the mean absorbed dose to the organ or tissue, weighted by an appropriate value of RBE for the biological end point of concern, should therefore be used. These RBE values may differ for different biological endpoints and different tissues or organs. Guidance on appropriate values of the RBE can be obtained in *Publication 58* (ICRP 1989b), NCRP Report No. 104 (1990) and *Publication 92* (ICRP, 2003c).

(B 25) As a consequence, the quantities, equivalent dose and effective dose, with their unit with the special name sievert (Sv), should not be used in the quantification of radiation doses or in determining the need for any treatment in situations where tissue reactions are caused. In general, in such cases doses should be given in terms of absorbed dose in gray (Gy), and if high-LET radiations (e.g., neutrons or alpha particles) are involved, an RBE-weighted dose, RBE·D (Gy), may be used. The RBE value to be considered depends, however, not only on the type and energy of the particles involved but also may depend on dose and dose rate in the specific situation and on the tissue as well as organs. In such cases it is necessary to clearly state which RBE value has been applied.

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B.2.3. References, Section B.2

ICRP, 1964. Recommendations of the International Commission on Radiological Protection. ICRP Publication 6. Pergamon Press, Oxford, UK.

ICRP, 1977. Recommendations of the International Commission on Radiological Protection. ICRP Publication 26. Ann. ICRP 1 (3).

ICRP, 1989b. RBE for deterministic effects. ICRP Publication 58. Ann. ICRP 20 (4).

ICRP, 1991b. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21 (1–3).

ICRP, 2003a. Biological effects after prenatal irradiation (embryo and fetus). ICRP Publication 90. Ann. ICRP 33 (1/2).

ICRP, 2003c. Relative biological effectiveness (RBE), quality factor (Q), and radiation weighting factor (w_R). ICRP Publication 92. Ann. ICRP 33 (4).

NCRP, 1990. The Relative Biological Effectiveness of Radiations of Different Quality. NCRP Report No. 104. National Council on Radiation Protection and Measurements, Bethesda, MD.

Streffer, C., Bolt, H., Follesdal, D., et al., 2004. Low Dose Exposures in the Environment – Dose-Effect Relations and Risk Evaluation. Springer, Berlin-Heidelberg-New York-Hong Kong-London-Milan-Paris-Tokyo.

UNSCEAR, 2000. Sources and Effects of Ionizing Radiation. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation. Volume II: Effects. United Nations, New York.

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B.3. Quantities in radiological protection

(B 26) Radiological protection has the general aim of protecting humans and the environment from harm caused by ionising radiation after external as well as internal exposures. This requires a quantitative description of the radiation fields external to and internal within the human body. Similar considerations apply to protection of other biological organisms. This latter aspect will not be considered further in this Annex.

(B 27) While radiation fields external to the body can be well described by physical quantities such as particle fluence or air kerma free in air, the internal radiation fields following the intake of radionuclides depend upon their biokinetics and on anatomical and physiological parameters of the human body.

(B 28) Fluence is a quantity used to describe external radiation fields. It is not, however, practicable for general use in radiological protection and the definition of limits. Fluence always needs the additional specification of the particle and particle energy as well as direction distributions. Its correlation with detriment is complex.

(B 29) As mentioned in the Introduction, in radiological protection practice, a single quantity has been developed for specifying the 'amount' of exposure which is quantitatively related to the probability of stochastic effects in human bodies for all types of radiations regardless of which type of ionising radiation is considered or whether the radiation is incident on the body or emitted by radionuclides within the body. It needs to be stressed that this is a practical protection quantity that involves parameter values that are based on judgement.

(B 30) The initial step in the interaction of ionising radiation with biological material is energy transfer that leads to ionisations. It might appear reasonable to use the amount of absorbed energy per unit of mass (absorbed dose) as the only term for quantifying the radiation exposure in radiological protection in order to estimate the risk caused by a given exposure. This is not sufficient, however, as radiation effects depend not only on the absorbed dose but also on the type of radiation, on the distribution of energy absorption in time and space within the human body, and on the radiosensitivity of the exposed tissues or organs.

(B 31) The basic procedure of dose assessment adopted by the Commission is to use *absorbed dose* as the fundamental physical quantity, to average it over specified organs and tissues, and to apply suitably chosen weighting factors to take account of differences in biological effectiveness of different radiations and of differences in sensitivities of organs and tissues to stochastic health effects. *Effective dose* is therefore a quantity based on the internal and external radiation fields and the primary physical interactions in human tissues as well as on judgements about the biological reactions resulting in stochastic health effects.

B.3.1. Fluence and kerma

(B 32) A radiation field of a specific type is fully described by the number N of particles, their distributions in energy and direction, and their spatial and temporal

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distribution. This requires the definition of scalar and vector quantities. Definitions of radiation field quantities are given in detail in ICRU Report 60 (1998). While vector quantities providing information on direction distributions are mainly applied in radiation transport theory and calculations, scalar quantities such as particle fluence or kerma are often used in dosimetry applications.

(B 33) Radiation field quantities are defined at any point in a radiation field. There are two classes of radiation field quantities referring either to the number of particles, such as fluence and fluence rate, or to the energy transported by them, such as energy fluence. Radiation fields may consist of various types of radiation, and those field quantities which are based on particle numbers are always related to a specific type. This is often expressed by adding the particle name to the quantity, e.g., neutron fluence.

(B 34) The quantity fluence is based on the concept of counting the number of particles incident or passing a small sphere.

(B 35) The *fluence*, Φ, is the quotient of $\mathrm{d}N$ by $\mathrm{d}a$, where $\mathrm{d}N$ is the number of particles incident upon a small sphere of cross-sectional area $\mathrm{d}a$, thus

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a} \tag{B.3.1}$$

The fluence is independent of the direction distribution of the particles entering the sphere. In calculations, fluence is often alternatively expressed in terms of the length of trajectories of particles passing through a small volume $\mathrm{d}V$. The fluence, Φ, is then given by

$$\Phi = \frac{\mathrm{d}l}{\mathrm{d}V} \tag{B.3.2}$$

where $\mathrm{d}l$ is the sum of the lengths of trajectories through this volume $\mathrm{d}V$.

(B 36) In radiation fields the number of particles traversing a small sphere is always subject to random fluctuations. However, fluence – as well as related quantities – is defined as a non-stochastic quantity and hence has a single value at a given point and time with no inherent fluctuations. Its value should be considered as an expectation value.

(B 37) The transfer of energy from uncharged particles (indirectly ionising particles, e.g., photons or neutrons) to matter is performed by the liberation and slowing down of secondary charged particles in this matter. This led to the definition of the quantity kerma. The *kerma*, K, is the quotient of $\mathrm{d}E_{\mathrm{tr}}$ by $\mathrm{d}m$, where $\mathrm{d}E_{\mathrm{tr}}$ is the sum of the kinetic energies of all charged particles liberated by uncharged particles in a mass $\mathrm{d}m$ of material. It is given by:

$$K = \frac{\mathrm{d}E_{\mathrm{tr}}}{\mathrm{d}m} \tag{B.3.3}$$

(B 38) The SI unit of kerma is J kg^{-1} and its special name is gray (Gy). Kerma is a non-stochastic quantity in which $\mathrm{d}E_{\mathrm{tr}}$ is seen to be the expectation value of the sum of energies of liberated charged particles.

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B.3.2. Absorbed dose

(B 39) In radiation biology, clinical radiology and radiological protection the absorbed dose, D, is the basic physical dose quantity. It is used for all types of ionising radiation and any irradiation geometry.

(B 40) Absorbed dose, D, is defined as the quotient of $\mathrm{d}\bar{\varepsilon}$, by $\mathrm{d}m$, where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted to matter of mass $\mathrm{d}m$ by ionising radiation, that is

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m} \tag{B.3.4}$$

The SI unit is J kg^{-1} and its special name is gray (Gy). While the value of kerma depends only on interactions in the material of mass element $\mathrm{d}m$, the value of absorbed dose also depends on the secondary charged particles which are released in the surroundings of the mass element $\mathrm{d}m$ and which enter this element. Absorbed dose is derived from the mean value of the stochastic quantity of energy imparted, ε, and does not reflect the random fluctuations of the interaction events in tissue. While it is defined at any point in matter, its value is obtained as an average over $\mathrm{d}m$ and hence over many atoms or molecules of matter.

(B 41) The definition of absorbed dose has the scientific rigour required for a basic physical quantity. It implicitly takes account of the radiation field as well as of all of its interactions with matter inside and outside the specified volume. It does not, however, take account of the atomic structure of matter and the stochastic nature of the interactions. Absorbed dose is a measurable quantity and primary standards exist to allow its determination by measurement.

(B 42) A particular feature of ionising radiations is their discontinuous interaction with matter and the related stochastic (probabilistic) nature of energy deposition. Energy is transferred to the tissue by charged particles in interactions with individual atoms and molecules. The human body is made up of organs and tissues, which consist of cells, sub-cellular structures and macromolecules such as DNA. Absorbed dose is defined as the mean of the stochastic distribution of energy deposited in a volume element. The fluctuations of energy deposited in individual cells and sub-cellular structures and the microscopic tracks of charged particles are the subject of *microdosimetry*.

(B 43) The magnitude of the fluctuations of energy deposited in different small tissue volumes depends on the value of the absorbed dose and on the size of the volume considered. At a given dose, these fluctuations increase with increasing ionisation density in charged particle tracks (characterised by the linear energy transfer, LET, see Section B.3.5, paragraphs B 73 – B 131) of the radiation. At the low absorbed doses generally of concern in radiological protection, the statistical fluctuation of energy deposited can be substantial between individual cells and within a single hit cell. This is the case particularly for densely ionising radiations (high-LET radiation) such as alpha particles and secondary charged particles from neutron interactions.

(B 44) At a given absorbed dose, the actual value of energy imparted, ε, in a small tissue volume, e.g., in a single cell, is given by the sum of energies deposited in that

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volume by all individual events. In any volume, fluctuations of ε are caused by variation in the number of events and by variation in the energy deposited in each event. For low-LET radiations (e.g., photons and electrons) the energy imparted in each event (hit) is relatively low, and at low doses more cells experience energy deposition events than in the case of exposure to high-LET radiation at the same dose. As a consequence, the fluctuation in the energy deposited among cells is smaller for low-LET than for high-LET radiation.

(B 45) (B 45) For low mean doses of high-LET radiation (e.g., charged particles from neutron interactions or alpha particles), the frequency of hits in most cells is zero, in a few it is one and exceptionally it can be more than one. The value of energy deposited in most individual cells is then zero but in the 'hit' cells it can exceed the mean value (i.e., absorbed dose) in the tissue by orders of magnitude. Even among the hit cells the distribution of these events is very heterogeneous. These large differences in the energy deposition distribution in microscopic regions for different types (and energies) of radiation have been correlated to observed differences in biological effectiveness or radiation quality (Goodhead, 1994). Further information is given, for example, in the UNSCEAR 1993 and 2000 reports (UNSCEAR, 1993; 2000).

(B 46) Auger electrons emitted from radionuclides in the body need special attention if such emitters are in or near to the DNA. Often a radionuclide, which decays via internal conversion, emits many Auger electrons. These emissions can result in a very localised energy deposition, and the biological effect may, therefore, be similar to that of a high-LET radiation. This has already been considered in *Publication 60* (ICRP, 1991b); see Section B.3.5., paragraphs B 86 – B 99).

(B 47) In the definition of radiological protection quantities no attempts are made to specify the stochastic distribution of physical processes at a microscopic level. Instead of explicitly considering such distribution functions, a pragmatic and empirical approach has been adopted to take account of radiation quality differences. Radiation weighting factors take into account the effects due to differences in distribution of energy deposited in microscopic regions through judgements based on the results of radiobiological experiments. This is discussed in more detail in Section B.3.5, paragraphs B 73 – B 131.

B.3.3. Averaging of absorbed dose

(B 48) As described above, the quantity absorbed dose is defined to give a specific value at any point in matter. However, in practical applications absorbed doses are often averaged over larger tissue volumes. It is thus assumed that, for low doses, the mean value of absorbed dose in a specific organ or tissue can be correlated with radiation detriment from stochastic effects in all parts of that organ or tissue with sufficient accuracy for the purposes of radiological protection.

(B 49) The mean absorbed dose in the region of an organ or tissue T, $\overline{D}_{\mathrm{T}}$, is defined by

$$\overline{D}_{\mathrm{T}} = \frac{\int_{\mathrm{T}} D(x,y,z)\rho(x,y,z)\mathrm{d}V}{\int_{\mathrm{T}} \rho(x,y,z)\mathrm{d}V} \qquad \text{(B.3.5)}$$

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where V is the volume of the tissue region T, D the absorbed dose at a point (x,y,z) in that region and ρ the mass density at this point. In practice, the mean absorbed dose in an organ or tissue T, $\overline{D}_T$, is usually written D_T.

(B 50) The averaging of absorbed doses in different tissues or organs of the human body and their weighted sum are the basis for the definition of the protection quantities which are used for limiting stochastic effects at low doses. This approach is based upon the assumption of a linear-non-threshold, dose–response relationship (LNT model) and allows the addition of doses from external and internal exposure. This concept is considered to be an acceptable approximation for radiological protection purposes and was first adopted by the Commission in *Publication 9* (ICRP, 1966). It was subsequently reaffirmed in later Recommendations including *Publications 26* and *60* (ICRP, 1977, 1991b) and is further supported in Annex A of the present Recommendations. The definitions of all the protection quantities rely on this fundamental assumption of the LNT model in the low-dose region.

(B 51) The averaging of absorbed dose is carried out over the volume of a specified organ (e.g., liver) or tissue (e.g., muscle) or a region of a tissue (e.g., endosteal surfaces of the skeleton, skin). The extent to which the mean absorbed dose (Eqn. B.3.5) is representative of the local absorbed dose throughout organs, tissues, or tissue regions depends on a number of factors. For external radiation exposure, this depends mainly on the homogeneity of the exposure and on the penetrability or range of the incident radiation in the body. For penetrating radiation (photons, neutrons) the absorbed dose distribution within most organs may be sufficiently homogeneous, and thus the mean absorbed dose is a suitable measure of the dose throughout the organ or tissue.

(B 52) The absorbed dose distribution within the specified organ or tissue may be very heterogeneous for radiation with low penetration or limited range (low-energy photons, charged particles) as well as for widely distributed tissues and organs (e.g., active [red] bone marrow or lymphatic nodes) in non-homogeneous radiation fields. In cases of extreme partial body exposure tissue damage may occur even if the mean tissue or organ dose or the effective dose is below the dose limit. For example, this may occur in the case of exposure of the skin to low-penetrating radiation. A special limit is applied to local skin dose to avoid tissue reactions (see Section B.5.5).

(B 53) For radiations emitted by radionuclides retained within body organs or tissues, so-called internal emitters, the absorbed dose distribution in the organs depends on the distribution of the radionuclides and the penetration and range of the radiations emitted. It also depends on the structure of the organ or tissue (e.g., 'walled' organs such as the urinary bladder, airways of the respiratory tract, and the highly heterogeneous mixture of bone mineral, inactive and active bone marrow). The absorbed dose distribution for radionuclides emitting alpha particles, soft beta particles, low-energy photons, or Auger electrons may be highly heterogeneous.

(B 54) This heterogeneity occurs in particular in the case of radionuclides deposited in the respiratory tract (e.g., radon decay products on the bronchial mucosa), passing through the alimentary tract, or deposited on bone surfaces (e.g., plutonium and related elements) or on skin. In such situations the mean absorbed dose averaged over the entire organ or tissue is not considered to be an appropriate dose quantity

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for estimating the probability of stochastic damage. The Commission has addressed this issue and has developed dosimetric models for the respiratory system (ICRP, 1994a), the alimentary tract (ICRP, 2006c), and the skeleton (ICRP, 1979) that take account of the distribution of radionuclides and the location of sensitive cells in the calculation of mean absorbed dose to these tissues. In these cases the dose determined in the identified tissue region considered to be the target for the development of radiation-induced cancer is treated as the average dose.

(B 55) As discussed above, the heterogeneous distribution of energy deposition is of concern with respect to the averaging procedure in the low dose range and especially with radionuclides which are heterogeneously distributed in an organ or tissues and which emit particles with short ranges. However, no established approaches are presently available for use in radiological protection practice which take into account microdosimetric considerations or the three-dimensional track structure in tissues and the related energy deposition. Considering the stochastic nature of the induction of cancer and of heritable disease and the assumptions that one single track of ionising particles may be sufficient for the initiation process, it appears that the present approach is pragmatic for radiological protection purposes with a justified scientific basis. The uncertainty associated with such an approach should be kept in mind.

(B 56) In the case of deposition of 'hot particles' in the lung or other tissues, (e.g., aerosols deposited in the lung with low solubility and high specific activity) the Commission continues to consider that the associated hazard of malignant disease induction is similar to or lower than that from homogenous distribution of equal activity in the lungs (Lafuma et al., 1974, ICRP, 1980, Charles et al., 2003).

(B 57) Dose distributions that are highly heterogeneous can result from the incorporation of DNA precursors labelled with tritium (e.g., thymidine, deoxycytidine) or Auger emitters incorporated into DNA in cell nuclei. Owing to the specific location of the emitter and the very short range of tritium beta radiation and Auger electrons, cell nuclei can be exposed to doses which are much higher than the mean dose to the cell or the organ or tissue. Tritiated DNA precursors may therefore be more radiotoxic than tritiated compounds, such as tritiated water, which are not specifically located in the cell nucleus (Streffer et al., 1978). In such cases, risks might be estimated on the basis of dose to cell nuclei. Another approach is to take account of experimental mammalian data on the relative biological effectiveness of heterogeneously distributed radionuclides (e.g., tritiated thymidine) compared with the same nuclides distributed more uniformly (e.g., tritiated water) (Streffer et al., 1978) or with external irradiation. The Commission is not proposing a specific scheme for the treatment of doses and risks from such localised nuclear irradiation (see Section B.3.5, paragraphs B 86 – B 99).

B.3.4. Equivalent dose and effective dose

(B 58) The protection quantities are used to specify dose limits to ensure that the occurrence of stochastic health effects is kept below unacceptable levels and tissue reactions are avoided. The system of protection quantities is shown in Figs B.1

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and B.2. Their definition is based on the mean absorbed dose, $D_{T,R}$, in the volume of a specified organ or tissue, T, due to the radiation of type R – or in another specified target region of the body – (see Eqn. B.3.5). The radiation R is given by the type and energy of radiation either incident on the body or emitted by radionuclides residing within the body. The protection quantity *equivalent dose* in an organ or tissue, H_T, is then defined by

$$H_T = \sum_R w_R D_{T,R} \tag{B.3.6}$$

where w_R is the radiation weighting factor for radiation R (see Section B.3.5, paragraphs B 73 – B 131, and Table B.4). The sum is performed over all types of radiations involved. The unit of equivalent dose is J kg^{-1} and has the special name sievert (Sv).

(B 59) Values of w_R are mainly based upon experimental data of the relative biological effectiveness (RBE) for various types of radiations at low doses (see Section B.3.5, paragraphs B 73 – B 131). A set of w_R values for various radiations was given in *Publication 60* (ICRP, 1991b); cf. Table B.3. The general concept of these radiation weighting factors remains unchanged. Some modifications to the values of w_R adopted in *Publication 60* (ICRP, 1991b) are provided and discussed in Section B.3.5, paragraphs B 73 – B 131 (see Table B.4).

(B 60) The effective dose, E, introduced in *Publication 60* was defined as:

$$E = \sum_T w_T \sum_R w_R D_{T,R} = \sum_T w_T H_T \tag{B.3.7}$$

where w_T is the tissue weighting factor for tissue T (see Section B.3.5, paragraphs B 132 – B 145, and Table B.2) and $\Sigma w_T = 1$. The sum is performed over all organs and tissues of the human body considered in the definition of E and for which w_T

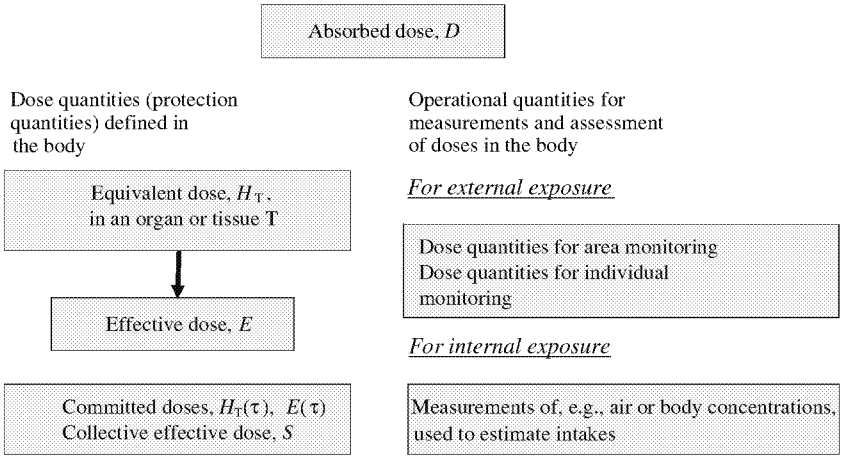

Fig. B.2. System of protection and operational quantities for use in radiological protection.

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Table B.3. Radiation weighting factors[1] (ICRP 1991b).

Type and energy range[2]	Radiation weighting factors, w_R
Photons, all energies	1
Electrons and muons, all energies[3]	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, energy>2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

[1] All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

[2] The choice of values for other radiations is discussed in paragraph A14 in ICRP (1991b).

[3] Excluding Auger electrons emitted from nuclei bound to DNA (see paragraph A13 in ICRP 1991b).

Table B.4. Radiation weighting factors[1] in the 2007 Recommendations.

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous curve as a function of neutron energy (see Fig. B.4 and Eqn. B.3.16)

[1] All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

values are given in Table B.2. The unit of effective dose is J kg^{-1} with the special name sievert (Sv). The same unit used for equivalent dose and effective dose is also used for the operational dose quantities (see Section B.4.1, paragraphs B 159 – B 170). Care must be taken in ensuring that the quantities being used are clearly stated.

(B 61) While absorbed dose in a specified tissue is a physical quantity, the equivalent dose and effective dose include weighting factors which are based on radio-

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biological and epidemiological findings. These weighting factors are selected for application in radiological protection by judgement and include acceptable simplifications (see Section B.3.5). Therefore the definition and the value of effective dose are not based on physical properties only. For example, the tissue weighting factors, w_T, are based on epidemiological studies of cancer induction as well as on experimental genetic data after radiation exposure, and on judgements. Furthermore they represent mean values for humans, averaged over both sexes and all ages.

(B 62) The definition of the effective dose is based on the mean doses in organs or tissues of the human body. The quantity provides a value which takes account of the given exposure situation but not, however, the characteristics of a specific individual. For internal exposure of humans, for example, the organ doses are often determined by assessing the intake of incorporated radionuclides and applying dose coefficients which relate the intake of activity to the corresponding mean organ doses. These coefficients are calculated using general biokinetic models and reference phantoms. Hence this means that, for a given incorporated activity of a specific radionuclide, the corresponding effective dose is estimated. This approximation of the dose is judged to be acceptable for radiological protection purposes.

(B 63) The use of effective dose allows exposures in very different situations (e.g., internal and external exposure by different types of radiation) to be combined in a single value. As a consequence, the primary exposure limits can be expressed in terms of a single quantity. This facilitates the system of dose limitation and record-keeping.

(B 64) In order to provide a practicable approach for the assessment of effective dose, coefficients relating it to physical quantities, e.g., particle fluence or air kerma for external exposure or activity intake for internal exposure, are calculated for standard conditions (e.g., mono-energetic radiations, standard irradiation geometries, selected chemical compounds labelled with radionuclides, models for the transfer of radionuclides in the body) in anthropomorphic phantoms with clearly defined geometries. These phantoms include most organs and tissues in the body, especially those listed in the table of the tissue weighting factors (Table B.2).

(B 65) In the Commission's publications since *Publication 26* (ICRP, 1977), the calculation of effective dose (or effective dose equivalent) from external radiation and from radionuclides incorporated into the body has been based on the equivalent dose to organs and tissues derived from sex-invariant anatomical and biokinetic models weighted by the sex-averaged tissue weighting factors (ICRP, 1994b). The scheme of calculation has now changed further with the development of male and female phantoms (Section B.5.2).

(B 66) For the calculation of conversion coefficients relating effective dose to radiation field quantities (for external radiation exposure situations), e.g., air kerma or particle fluence, ICRP departed from this approach in *Publication 74* (ICRP, 1996b), as sex-specific anatomical models were used. The following formula with sex-specific equivalent doses in organs and tissues for the calculation of effective dose was applied in *Publication 74*:

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$$E = w_{\text{breast}} H_{\text{breast,female}} + \sum_{\text{T} \neq \text{breast}} w_{\text{T}} \left[\frac{H_{\text{T,male}} + H_{\text{T,female}}}{2} \right] \tag{B.3.8}$$

where the summation includes the dose to the gonads (ovaries in the female, testes in the male). The different procedures (using sex specific or hermaphrodite models), however, yield values of effective dose which are not very different and are sufficiently precise for applications in radiological protection.

(B 67) The Commission has defined adult male and female computational phantoms (see Section B.5.2). These models will be used for calculations of dose conversion coefficients for external and of dose coefficients for internal radiation exposures. The use of sex-specific computational models allows the calculation of the male and female organ doses from which the averaged equivalent dose is calculated and used for the calculation of the effective dose. This can be done for the doses to the breast and the gonads in the same way as with the other organs and tissues.

(B 68) The procedure adopted to determine the tissue weighting factors is to first assess the risks of radiation-induced stochastic effects in males and females separately, then calculate sex specific radiation detriment and from these values give sex-averaged w_{T} values (Annex A). The sex-averaged w_{T} values, as well as the sex-averaged organ and tissue doses, are then used for the calculation of the effective dose (Fig. B.3). Under these conditions it is not reasonable to treat the contribution of the male and female doses separately in the calculation of effective dose. All tissues can be treated according to Eqn. (B.3.9).

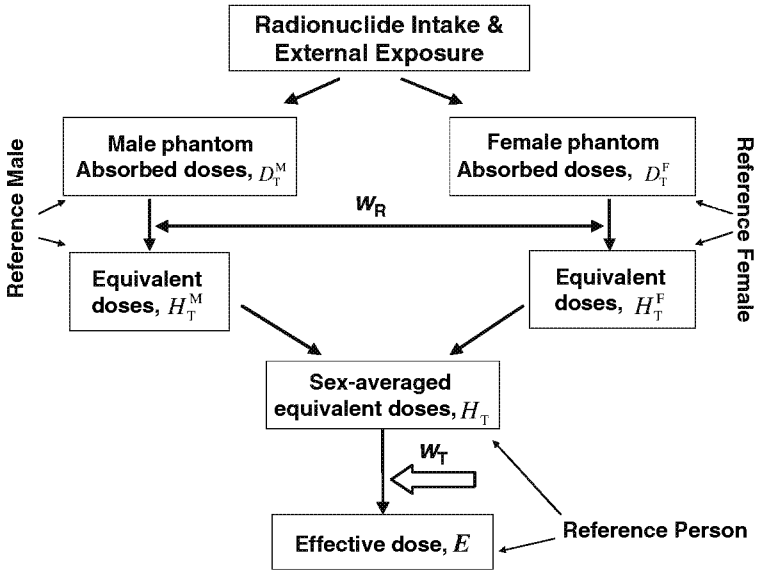

Fig. B.3. Sex – averaging in the calculation of effective dose (E).

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(B 69) The effective dose E is then computed from the equivalent dose assessed for organ or tissue T of the Reference Male, H_T^M, and Reference Female, H_T^F, including the remainder tissues (see Section B.3.5, paragraphs B 132 – B 145, and Eqn. B.3.17), as in the following equation:

$$E = \sum w_T \left[\frac{H_T^M + H_T^F}{2} \right] \tag{B.3.9}$$

This equation together with the new female and male reference phantoms (see Section B.5.2 and Figs B.2 and B.3) will be used for the future calculation of conversion coefficients and dose coefficients.

(B 70) For practical use, the calculation of organ doses or conversion coefficients in cases of external exposures and of dose coefficients (dose per intake, Sv Bq^{-1}) in cases of internal exposures is not based on data from individual persons but on reference values for the human body given in *Publication 89* (ICRP, 2002). In addition, age-specific data, e.g., food consumption etc., may need to be considered for assessment of exposures for members of the public. The use of reference values and the averaging over both sexes in the calculation of effective dose indicates that the reference dose coefficients are not aimed at providing a dose for a specific individual but for a Reference Person. Reference computational phantoms for children of various ages will also be developed for use in the calculation of dose coefficients for members of the public.

B.3.5. Weighting factors

(B 71) As noted previously, mean absorbed dose is insufficient, on its own, for assessing detriment caused by ionising radiation exposure. In order to establish a correlation between dose quantities applied in radiological protection and stochastic effects (radiation-induced cancer and heritable diseases), two types of weighting factors have been introduced, a radiation weighting factor, w_R, and a tissue weighting factor, w_T.

(B 72) The weighting factors are intended to take account of different types of radiation and of stochastic effects in different organs and tissues of the body. They are therefore broadly based on a wide range of experimental data and epidemiological studies and they are taken to be independent of age and sex. In *Publication 60* (ICRP, 1991b) the Commission selected a general set of these weighting factors that were considered to be appropriate for the needs of radiological protection (Tables 1 and 3). This procedure is maintained in these 2007 Recommendations.

Radiation weighting factors

(B 73) The method of radiation weighting in the definition of radiological protection quantities has been used since the early 1960s. Before 1991, this was achieved by applying the quality factor concept using a specified $Q(L)$ function (ICRP, 1977). In *Publication 60* (ICRP, 1991b), radiation weighting was defined differently for the

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protection quantities and for the operational dose quantities used in measurements of external exposure.

(B 74) Radiation weighting is based mainly on an evaluation of the relative biological effectiveness (RBE) of the different radiations with respect to stochastic effects. The RBE is used in radiobiology for characterising the different biological effectiveness of radiations. RBE values are given as the ratio of the absorbed doses of two types of radiation producing the same specified biological effect in identical irradiation conditions (dose value of a reference radiation divided by the corresponding dose value of the considered radiation which causes the same level of effect).

(B 75) RBE values for a specific radiation depend upon the conditions of exposure including the biological effect investigated, the tissue or cell type involved, the dose and the dose rate, and the dose fractionation scheme; therefore, for a given type and energy of radiation, there will be a range of RBE values. The RBEs reach maximum values (RBE_M) at low doses and low dose rates. RBE_M is therefore of particular interest for defining radiation weighting factors for use in radiological protection. The weighting factors are taken to be independent of the dose and dose rate in the low-dose region.

(B 76) The concepts of the quality factor and radiation weighting are based on differences in the biological effectiveness of the various types of radiation which have their origin in the differences of their energy deposition properties along the tracks of charged particles. For applications in radiological protection, the complex structure of the charged particle tracks in tissue is characterised by a single parameter only, the unrestricted linear energy transfer, L_∞, (often denoted linear energy transfer, *LET* or L), and the quality factor Q is defined by a function of L as given in various publications of ICRP and ICRU (ICRP, 1963, 1977, 1991b, ICRU, 1970, 1986) – for more details, see Section B.4.2.

(B 77) Another feature of the energy transfer of low- and high-LET particles is the difference in the event distribution as has already been mentioned and discussed in Section B.3.2. This effect influences their biological effectiveness.

(B 78) Radiation weighting factors, w_R, have been specified in the definition of the protection quantities since *Publication 60* (ICRP, 1991b). They are factors by which the mean absorbed dose in any tissue or organ is multiplied to account for the detriment caused by the different types of radiation relative to photon radiation. Numerical values of w_R are specified in terms of type and energy of radiations either incident on the human body or emitted by radionuclides residing within it. Values of w_R adopted in *Publication 60* (ICRP, 1991b) are given in Table B.3.

(B 79) The same values of the radiation weighting factors, w_R, are applied to all tissues and organs of the body, independent of the fact that the actual radiation field varies owing to attenuation and degradation of the primary radiation and the production of secondary radiations of different radiation quality. The value of w_R may therefore be seen as a factor representing radiation quality averaged over the different tissues and organs of the body.

(B 80) The averaging procedure implied in the determination of w_R has raised some concern, especially in the case of external low-energy neutron radiation exposure where secondary photons (low-LET radiation) contribute significantly to tissue

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and organ doses (Dietze and Alberts, 2004). Therefore the mean radiation quality in a tissue or organ exposed to low-energy neutrons depends on its position in the body and varies with the direction of incidence on the body.

(B 81) This problem of bi-locality of specifying radiation quality and absorbed dose is discussed in detail in *Publication 92* (ICRP, 2003c). That report proposes how to achieve an improved radiation weighting factor for high-LET particles, and a modified function is given. A fixed relationship is proposed between the radiation weighting factor and a mean quality factor averaged over the human body and calculated for isotropic exposure. The present 2007 Recommendations do not, however, fully follow the procedure proposed in *Publication 92*. Details are given in Section B.3.5, paragraphs B 100 – B 115.

(B 82) Ideally the determination of w_R values would be predominantly based on RBE data from in-vivo investigations related to stochastic effects. Often cancer and leukaemia induction or life shortening after whole-body exposure has been determined. While in-vitro investigations with cells can provide important contributions to the understanding of basic mechanisms regarding carcinogenesis, the RBE values obtained in such studies may not be well correlated with carcinogenesis in humans. In many cases, however, there are only limited data available from in-vivo investigations on animals for the range of radiation qualities of interest in radiological protection. Therefore the $Q(L)$ function which is mainly based on data from in-vitro experiments (NCRP, 1990) is used where necessary as the basis of the calculation of a mean Q-value for the human body which in turn is then used for estimating radiation weighting factor values. This is especially the case for protons and heavy ions, and to some extent for neutrons (ICRP, 2003c).

(B 83) Generally, a broad range of RBE values has been obtained in investigations of various biological effects which do not exhibit a direct relationship to the effects for which radiation weighting factors are required. Experimentally determined RBE values are often associated with large uncertainties due, for example, to the small numbers of animals used and many other influencing factors. The weighting factors are selected to give a representative value for the known data and to be sufficiently accurate for application in radiological protection. The values of w_R are selected by judgement for use in the determination of protection quantities; as such they have fixed values and are not associated with any uncertainty (see Section B.6).

(B 84) ***Reference radiation.*** Values of RBE obtained experimentally depend on the reference radiation chosen. Generally, low-LET radiation is taken as the reference, and mostly ^{60}Co- or ^{137}Cs-gamma rays or high-energy x rays, > 200 kV, have been used in experimental investigations. There exists, however, no international agreement on the choice of a specific photon type or energy as a general reference radiation. Therefore, for all RBE-related studies, information on the reference radiation used is needed.

(B 85) In *Publication 60* (ICRP, 1991b) the Commission adopted a radiation weighting factor of 1 for all photons (Table B.3). This is also proposed in *Publication 92* (ICRP, 2003c) and is consistent with the fact that no specific photon energy has been fixed as a reference. An average of RBE data related to photons of different energies is judged to be most appropriate for establishing w_R values for radiation

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protection. This approach does not, however, imply that no differences exist with respect to the biological effectiveness of photons of different energy (see Section B.3.5, paragraphs B 86 – B 99).

(B 86) ***Radiation weighting factors for photons, electrons, and muons.*** Photons, electrons, and muons are low-LET radiations with LET-values of less than 10 keV/μm. Low-LET radiations have always been given a radiation weighting of one. Before 1991 this was achieved by setting $Q(L) = 1$ for $L < 3.5$ keV/μm. *Publication 60* (ICRP, 1991b) defined $w_R = 1$ for these radiations, and $Q(L) = 1$ for $L < 10$ keV/μm for operational dose quantities (see Eqn. B.4.2). This has been decided mainly for practical reasons but also in consideration of the large uncertainties in estimating radiation risk factors which did not justify a more detailed description.

(B 87) Details on published RBE values for low-LET radiation are presented in *Publication 92* (ICRP, 2003c), and the consequences with respect to the weighting of photon radiations of different energies are discussed. Other publications also deal with this subject (e.g., SSK, 2005, Harder et al., 2004).

(B 88) In-vitro investigations of dicentric chromosome aberrations in human lymphocytes (Sasaki, 1991, Schmid et al., 2002, Guerrero-Carbajal et al., 2003), and for mutations and transformations in other cell lines, e.g., in human and human–hamster hybrid cells by Frankenberg et al. (2002), have shown that low energy x rays have a significantly larger RBE than ^{60}Co-gamma rays. In such experiments with cells, 20 kV x rays may be about 2 to 3 times as effective as conventional 200 kV x rays and these are about twice as effective as ^{60}Co gamma rays. In animal experiments, much lower ratios have been observed while epidemiological data are not sufficiently precise to see any differences.

(B 89) While photons of 1 to 5 MeV are less effective than x rays, as demonstrated by cellular effects in vitro, the situation may be different for very high energy photons, e.g., near high energy accelerators, or in radiation fields of cosmic rays. Such photons are able to produce secondary particles in nuclear interactions, e.g., neutrons or other high-LET particles. It can, therefore, not be excluded that the RBE value for these photons is higher than that of photons of about 1 to 5 MeV.

(B 90) The Commission stated in *Publication 60* (ICRP, 1991b) that 'simplicity is important to reflect our lack of precise information in man and an appreciation of the practical aspects of radiological protection. For example, the Commission does not believe it is helpful to adopt different quality-factor values for different photon energies.' More data is now available from investigations on cells showing significant differences in radiation quality of photons of different energies. However, there are additional practical arguments for keeping a single w_R value for all photons and electrons for the calculation of effective dose (Dietze and Alberts, 2004).

(B 91) In the case of external exposure to photons with energies from 30 keV to 5 MeV a proportion of the dose delivered to the organs is due to Compton-scattered photons in the body with an average energy significantly lower than that of the incident photons (Harder et al., 2004). Therefore, the variation of the mean RBE averaged over the human body for external photon radiations with different energies is expected to be smaller than the corresponding differences observed in investigations with thin cell layers in vitro (frequently mono-layers). Chen et al. (2005) have

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calculated the microdosimetric quantity, dose mean lineal energy, y_D, in small and large receptors, and have shown that the above-mentioned effect is not as large as assumed by Harder et al. (2004).

(B 92) Furthermore, external low-energy photon radiation (less than about 30 kV x rays) is strongly attenuated in tissue close to the surface of the body and its contribution to effective dose is generally small. An exception to this statement is the use of low-energy photons in radiodiagnostic procedures such as mammography. In this case of external exposure, however, the operational dose quantities $H^*(10)$ and $H_p(10)$ (see Sections B.4.3 and B.4.4) are used for radiation protection monitoring and for assessing effective dose. For photons with energies between 10 keV and 40 keV and frontal irradiation (AP) of the body, $H^*(10)$, is up to a factor 6 higher than E and, for other directions of radiation incidence (PA, LAT, ROT, ISO), this conservatism is even greater (ICRP, 1996b).

(B 93) In internal dosimetry, a single w_R value for all photons and electrons is a major simplification, but the arguments in support of this approach are the same as for external exposures. The special case of the probable greater effectiveness of short-range emissions from tritium and Auger emitters when the radionuclides are incorporated into DNA or otherwise localised in cell nuclei is discussed in Section B.3.3.

(B 94) However, the use of $w_R = 1$ for low-energy beta emissions from tritium is still the subject of scientific debate (CERRIE, 2004). Straume and Carsten (1993) provided a thorough review of experimental data on the carcinogenic, genetic, developmental and reproductive effects of exposure to tritiated water (HTO) and organically bound forms of tritium (OBT) in animals and in in-vitro cell systems. The spectrum of observed effects is indistinguishable from the effects of whole body external irradiation with x rays or gamma rays. Although the observed effects of tritium are very largely attributable to damage from ionising radiation, the transmutation of tritium to helium also has the potential to cause damage to DNA. The observed effects of tritium will include any contribution from such transmutation damage. Considering all observed effects of HTO exposure, RBE values were in the range 1–3.5. For comparisons with gamma rays, most values were between 1 and 3 while for x rays most were from 1 to 2, with values of 1–1.5 predominating. These measured RBEs for tritium beta irradiation are reasonably consistent with estimates based on microdosimetric considerations (Bigildeev et al., 1992, Morstin et al., 1993, Moiseenko et al., 1997).

(B 95) For the purposes of assessing risk at low chronic doses, studies of carcinogenesis are the most appropriate. These include studies of the acceleration of the appearance of mammary tumours in rats (Gragtmans et al., 1984) and the induction of acute myeloid leukaemia in mice (Johnson et al., 1995). Both these studies compared chronic exposure to HTO or to x rays (250 kVp) and gave RBE values of 1–1.3. In-vitro studies of transformation in 10T1/2 cells gave RBE values of up to about 2 compared to gamma rays.

(B 96) The RBE values obtained for beta emissions from tritium as HTO are within the range of values observed generally for low-LET radiations and therefore the simplified approach of using a single w_R value of 1 is applicable to tritium. The

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limited RBE data for OBT (organically bound tritium) show similar values to those for HTO in most cases (e.g., labelled amino acids) but higher values for tritiated DNA precursors. For example, Ueno et al. (1989) compared RBE values for HTO, ^{3}H-thymidine (^{3}HTdR) and ^{3}H-amino acids, measuring cell killing and mutation rates in mouse cells cultured in vitro. Doses were estimated on the basis of measurements of the ^{3}H content of cells and on the assumption that ^{3}HTdR was concentrated in the nucleus and that HTO and ^{3}H-amino acids had a uniform cellular distribution. On this basis for ^{3}HTdR a greater effect by a factor of 2 was obtained than for HTO and for ^{3}H-amino acids.

(B 97) The biological effects of Auger emitters have been extensively studied in a variety of in-vitro and in-vivo experimental systems (Bingham et al., 2000, Goddu et al., 1996). In vivo, rodent spermatogenesis has been utilised as a model system to evaluate the cytotoxicity of a range of Auger emitters including ^{55}Fe, ^{99m}Tc, ^{111}In, ^{114m}In, ^{123}I, ^{125}I, and ^{210}Tl. In vitro, the cytotoxic effects of ^{35}S, ^{75}Se, ^{51}Cr, ^{67}Ga, ^{77}Br, and a range of compounds labelled with ^{123}I and ^{125}I, have been studied in a variety of human and rodent cell lines and model culture systems. Representative of various results reported are an increase of biological effectiveness by a factor of 7–9 for ^{125}I when the radionuclide is incorporated into DNA following administration as ^{125}I-iododeoyuridine (^{125}IUdR), RBE values of around 4 for ^{125}I localised in the nucleus, but not directly bound to DNA, and RBE values of around 1 when ^{125}I is localised in the cytoplasm (Hofer et al., 1975; Howell et al., 1993; Kassis et al., 1989; Rao et al., 1990; Warters et al., 1978).

(B 98) Various dosimetric schemes have been proposed for Auger emitters, including the use of a w_R of 20 for the proportion of emitters bound to DNA where this is known (Howell et al., 1993). It is clear that assessment of doses and risks will require information on the distribution of radionuclides within tissues and cells, which will depend on the chemical form involved. It is only when the Auger emitter is concentrated in the nucleus that a significantly enhanced effect would be anticipated, compared with that evaluated on the basis of average tissue dose. The Commission recognises these uncertainties and has stated that Auger emitters will need analysis on a case-by-case basis.

(B 99) In summary, there are good arguments for the continued use of a w_R of 1 for all low-LET radiations for general radiological protection purposes. It is, however, important to note that this simplification is sufficient only for the intended application of assessing effective dose, e.g., for dose limitation, assessment and controlling of doses. It is not intended for retrospective assessment of individual risks of stochastic effects from radiation exposures. In such cases of individual retrospective dose assessment more detailed information on the radiation field (including the type of low-LET radiation) and appropriate RBE values may need to be considered if they are available (see Section B.5.8). Heterogeneity of dose within cells, as can occur with tritium or Auger emitters incorporated into DNA, may also require specific analysis.

(B 100) ***Radiation weighting factors for neutrons.*** The biological effectiveness of neutrons incident on the human body is strongly dependent on the neutron energy because of the variation of the secondary radiation with energy. Qualitatively, the following effects are important:

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- the production of secondary photons by neutron absorption in tissue which increases with decreasing neutron energy;
- the increase of the energy of recoil protons with increasing neutron energy;
- the release of heavier charged particles at higher neutron energies; and
- nuclear spallation processes at very high neutron energies.

(B 101) In *Publication 60* (ICRP, 1991b) the radiation weighting factor for neutrons has been given in two ways, by a step function defining five neutron energy ranges with w_R values of 5, 10, 20, 10, and 5 respectively (Table B.3, Fig. B.4), and by a continuous function for use in calculations. The tabulated values of w_R have generally not been used in practice; the continuous function has usually been applied. In radiation fields containing neutrons with a broad energy spectrum very often calculations using energy-dependent conversion coefficients are performed for estimating doses. All internationally recommended conversion coefficients, including those given in *Publication 74* (ICRP, 1996b) are based on the continuous function. Therefore, a continuous function is given here for defining radiation weighting factors for neutrons. It should be noted, however, that the use of a continuous function is based only on practical and computational considerations and does not imply the availability of more precise data.

(B 102) In *Publication 60* (ICRP, 1991b) a maximum value of 20 was fixed for w_R. In *Publication 92* (ICRP, 2003c) it is stated that, in the neutron energy region near 1 MeV, the maximum value of w_R of about 20 is still an acceptable approximation. This judgement is not based on a specific experimental value but rather reflects a representative value considering the broad range of RBE values from experimental animal data for carcinogenesis and life shortening obtained from investigations using

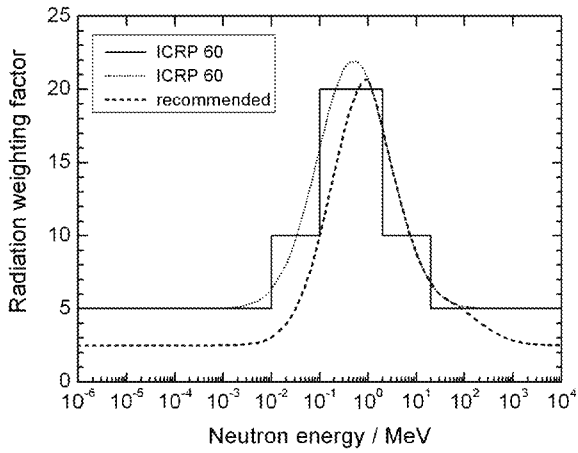

Fig. B.4. Radiation weighting factor, w_R, for neutrons versus neutron energy. Step function and continuous function given in *Publication 60* (ICRP 1991b) and function adopted in the 2007 Recommendations.

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fission neutrons from reactors (ICRP, 2003c). This value of 20 is, therefore, retained for neutron energies at about 1 MeV.

(B 103) When the human body is exposed to neutrons with energies below 1 MeV, a significant fraction of the absorbed dose is deposited by secondary photons mainly from the H(n, γ) reaction, which reduces the biological effectiveness. In this energy range this effect on RBE is much larger than the influence of the change in the LET-distribution of the neutron-produced secondary charged particles, mainly protons.

(B 104) When RBE data for fission neutrons or low-energy neutrons obtained from investigations with small animals are used as the basis for the evaluation of w_R values for human exposure, it should be recognised that the dose contribution from secondary photons in the human body is higher than in small animals such as mice (Dietze and Siebert, 1994). The photons are mainly produced by the capture of degraded neutrons, predominantly in hydrogen, and their contribution to the total equivalent dose in an organ is strongly dependent on the body size and on the position of the organ in the body. At the time of *Publication 60* (ICRP, 1991b) data from calculations with neutrons in anthropomorphic phantoms were not available, and data calculated for the ICRU sphere were used instead. It has been shown (ICRP, 2003c, SSK, 2005) that for neutrons below about 1 MeV, the consideration of the secondary photons in an anthropomorphic phantom results in considerably lower values for mean quality factors, and thus of w_R, than those given in *Publication 60*.

(B 105) In *Publication 92* (ICRP, 2003c), it is suggested that the dependence of the radiation weighting factor on neutron energy should be based on the $Q(L)$ function defined in *Publication 60* (ICRP, 1991b) and the calculation of a human body averaged mean quality factor q_E (see Eqn. B.3.10). The relationship between q_E and the weighting factor w_R is given there by a function

$$w_R = 1.6(q_E - 1) + 1 \tag{B.3.10}$$

This equation preserves a value of w_R of about 20 at neutron energies near 1 MeV. Calculations of q_E have been performed taking the dose distribution in the human body into account and using the tissue weighting factors w_T of the different organs and tissues by the equation

$$q_E = \sum_T w_T Q_T D_T / \sum_T w_T D_T \tag{B.3.11}$$

where Q_T is the mean quality factor in the tissue or organ T, and D_T the corresponding mean absorbed dose. Owing to the different w_T values of the organs and tissues not being symmetrically distributed in the human body, the value of q_E depends on the directional incidence of the radiation on the body. The calculations have shown that, for thermal neutrons, the deduced w_R (Eqn. B.3.10) may vary from 2.5 (for ISO and ROT incidence) to 3.2 (for AP incidence) for the various exposure conditions, and that there are also differences depending on the sex of the selected model (Kellerer et al., 2004). In general, the value of q_E depends also on the model of the human body, e.g., if the calculations are performed with a MIRD-type phantom or a voxel type phantom (see Section B.5.2).

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(B 106) In principle, the proposal of defining a general relationship between w_R and a mean quality factor q_E for all types and energies of particles as given in Eqn. (B.3.10) is attractive, because it points more clearly to the common scientific basis of the concept of radiation weighting and quality factor used in the definition of the operational quantities. In practice, however, Eqn. (B.3.10) can only be applied to strongly penetrating external high-LET radiation, e.g., neutrons, high-energy protons and heavy ions with very high energies. A factor of 1.6 has been introduced in Eqn. (B.3.10) in order to fit the calculated w_R-value for 1 MeV neutrons to experimental data. It is questionable whether it is justified to extend this factor to other particles and energies with different secondary charged particle spectra. Another shortcoming of defining this general relationship is the fact that q_E depends on many parameters, such as the phantom selected, the w_T values, the exposure situation chosen and even the computer code used. Many parameters may give rise to changes in future while w_R should remain stable. Equation (B.3.10) is therefore to be used only as a guide in establishing values of w_R for neutrons.

(B 107) For neutron energies of less than 1 MeV a similar energy dependence of the radiation weighting has been obtained also by other considerations (SSK, 2005, Dietze and Harder, 2004) without using a fixed relationship between Q and w_R. The relationship is based on the assumption that, with neutron energies below 1 MeV, the energy dependence of the neutron weighting for the human body depends mainly on the dose contribution of secondary photons and that, for a small tissue probe, the mean RBE value for the neutron-induced high-LET component ($RBE_{high\text{-}LET}$, mainly determined by recoil protons, protons from N(n,p) and heavier ions) is approximately independent of neutron energy (Edwards, 1997, Sasaki, 1991, Schmid et al., 2003).

(B 108) For anterior-posterior radiation incidence the mean absorbed dose contribution from secondary photons $f_{low\text{-}LET}$ (low-LET component relative to the total dose) in the human body and the contribution from secondary charged particles (high-LET component) have been calculated by

$$f_{low\text{-}LET} = (\Sigma w_T D_T f_{low\text{-}LET,T})/(\Sigma w_T D_T) \text{ and} \tag{B.3.12}$$

$$f_{high\text{-}LET} = 1 - f_{low\text{-}LET} \tag{B.3.13}$$

where $f_{low\text{-}LET,T}$ is the relative absorbed dose contribution in the tissue or organ T from secondary low-LET radiation. For the calculation of a body-averaged relative biological effectiveness the following equation has been applied:

$$RBE_{av} = RBE_{high\text{-}LET}(1 - f_{low\text{-}LET}) + RBE_{low\text{-}LET} f_{low\text{-}LET} \tag{B.3.14}$$

where RBE_{av} is the resulting RBE properly averaged over the human body. This 'mixing rule' is applied in the neutron energy range from thermal up to 1 MeV. For the photon contribution a value of $RBE_{low\text{-}LET} = 1$ is taken, and for the high-LET component a mean value of $RBE_{high\text{-}LET} = 25$ is chosen which is consistent with experimental data on the induction of dicentric chromosomal aberrations in cells (Schmid et al., 2003) and animal data for tumour induction and life shortening (SSK, 2005). These selected RBE-values result in an RBE_{av} value of about 20 in

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the human body for neutrons of 1 MeV which is consistent with the value mentioned above. Depending on the exposure conditions chosen, the energy dependence of RBE_{av} is similar to that of w_R calculated by Eqn. (B.3.10) in the energy range from thermal up to 1 MeV neutrons.

(B 109) In view of all these considerations the following function is given for the definition of the radiation weighting factor in the energy range below 1 MeV:

$$w_R = 2.5 + 18.2 \exp[-(\ln E_n)^2/6] \text{ for } E_n < 1 \text{ MeV} (E_n \text{in MeV}) \qquad \text{(B.3.15)}$$

(B 110) Figure B.4 shows that, in the neutron energy range below 1 MeV, the values of w_R are lower than those given in *Publication 60* (1991b). The function fully reflects the effect of secondary photons in the body and is well related to the mean quality factor q_E as given in *Publication 92* (ICRP, 2003c).

(B 111) The energy range above 1 MeV needs different considerations. In this energy range, almost no new experimental data is available from investigations of animals. All existing experimental data either on animals or on cells, however, show a clear decrease of RBE with increasing neutron energy. This is consistent with calculations based on the $Q(L)$ function (ICRP, 2003c). If, however, the relationship between q_E and w_R as defined in Eqn. (B.3.10) were applied, this would result in an increase of w_R for neutrons of about 30% in the energy range between 5 MeV and 100 MeV relative to the data of the continuous function as defined in *Publication 60* (ICRP, 1991b). This difference is much less than the uncertainty of RBE values in this energy range. Therefore, from a practical point of view, it seems more appropriate not to apply minor changes to the existing function in this energy range, but to stay with the values defined in *Publication 60*.

(B 112) There is no published experimental data with animals for neutron energies above about 50 MeV. Some RBE data on the induction of dicentric chromosomes in human lymphocytes was published recently (Nolte et al., 2005). These data together with the calculations of Pelliccioni (1998, 2004), Yoshizawa et al. (1998), and Sato et al. (2003) have shown that the mean quality factor averaged over the human body decreases with increasing neutron energy to values of less than 5, and reaches values near to those of protons at very high energies above 1 GeV. While this topic may need more detailed considerations in the future, a continuous weighting factor function for neutrons is also used for energies above 50 MeV. Its value decreases with increasing energy from about 5.5 at 50 MeV to about 2.5 at 10 GeV. This function is fitted to the function for lower neutron energies at 50 MeV. The neutron energy dependence of the data published by Pelliccioni (1998, 2004), Yoshizawa et al. (1998), and Sato et al. (2003) has been used as a guideline for the higher energies.

(B 113) In summary, the following continuous functions are used for the calculation of radiation weighting factors for neutrons:

$$w_R = \begin{cases} 2.5 + 18.2\, e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0\, e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25\, e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases} \qquad \text{(B.3.16)}$$

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Obviously these functions are complex. They have been chosen as an empirical approach describing the weighting of neutrons over more than 10 decades of neutron energy. The detailed functions, however, should not be misinterpreted to reflect precisely the biological data which, in fact, show a broad range of RBE values depending on neutron dose, neutron dose rate and biological endpoint considered.

(B 114) The preceding extensive discussion of this important matter of energy dependence of w_R for neutrons can be summarised as follows:

- The new Recommendations adopt a w_R function for neutrons which is based upon that given in *Publication 92* (ICRP, 2003c) but takes into account additional data.

The function for w_R for neutrons is derived using the following criteria:

- A continuous w_R function is chosen instead of a step function (ICRP, 1991b) for practical reasons. This decision, however, is not the result of a higher precision of the available radiobiological data but is based on practical considerations.
- For neutrons of about 1 MeV a maximum w_R value of about 20 is retained as given in *Publication 60* (ICRP, 1991b) and in *Publication 92* (ICRP, 2003c).
- For neutron energies below about 1 MeV the shape of the curve for the energy dependence of w_R is generally based on that related to the mean quality factor q_E, as well as on the mean RBE_{av} expressed in Eqn. (B.3.14). The recommended w_R values are similar to those proposed in *Publication 92* (ICRP, 2003c).
- At energies above 50 MeV, for physical reasons w_R should asymptotically approach a value close to that of protons (for which some radiobiological data exist). Based on calculations by Pelliccioni (1998, 2004), Yoshizawa et al. (1998) and Sato et al. (2003) an asymptotic value of 2.5 at neutron energies above 1 GeV is chosen.

(B 115) The resulting function (Fig. B.4) is consistent with existing relevant physical and biological knowledge. The function does not establish a strict relationship between the mean quality factor and the radiation weighting factor for all neutron energies as proposed in *Publication 92* (ICRP, 2003c), and therefore there is not a fully common approach for protection and operational quantities, for the reasons given above. For radiological protection it appears, however, to be more important that the operational dose quantities for use in external exposure monitoring provide a good and conservative estimate of effective dose under most exposure conditions. This is achieved when applying the radiation weighting factors for neutrons as given in Eqn. (B.3.16).

(B 116) ***Radiation weighting factor for protons and pions.*** Only external radiation sources have to be considered for exposure to protons in practical radiological protection. In *Publication 60* (ICRP, 1991b) a radiation weighting factor of 5 was recommended for all protons with energies above 2 MeV except recoil protons (Table B.3).

(B 117) In recent years, proton radiation has received more attention owing to an increased interest in dose assessment for exposure to aircrew and to astronauts in space vehicles. In these cases the external proton radiation exposure is from solar and cosmic radiation. In the primary radiation fields, high energy protons strongly

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dominate, and protons with energy of a few MeV are of minor significance, even when considering the increasing biological effectiveness at low energies. The range of low-energy protons in tissue is small (range of protons in tissue: 4 MeV protons: 0.25 mm; 10 MeV protons: 1.2 mm) and they will mostly be absorbed in the skin.

(B 118) It is, therefore, judged to be sufficiently accurate for applications in radiological protection to adopt a single w_R value for protons of all energies. It is appropriate to rely on data for high energy protons as these are the most relevant in cosmic radiation fields.

(B 119) There are very few investigations using animals that give information on the RBE for high energy protons. Most measured RBE values are between 1 and 2. With respect to the ionisation density in tissue, high energy protons can be regarded as low-LET radiation (with a mean LET value much less than 10 keV/μm) and, applying the $Q(L)$ function from *Publication 60* (ICRP, 1991b), the mean quality factor of 100 MeV protons stopping in tissue is calculated to be less than 1.2 (ICRP, 2003c). At very high proton energies near 1 GeV, secondary charged particles from nuclear reactions become more important, and the mean quality factor increases up to about 1.8.

(B 120) Taking all considerations and available data into account, the radiation weighting factor adopted for protons in the new Recommendations is 2 (Table B.4).

(B 121) Pions are negatively or positively charged or neutral particles encountered in radiation fields at altitude in the atmosphere, resulting from interactions of the primary cosmic rays (predominantly high-energy protons) with nuclei in the atmosphere, thus contributing to the exposure of aircraft crew and passengers (approximately 0.1% of $H^*(10)$). They are also found as part of the complex radiation fields behind shielding of high-energy particle accelerators and thus may contribute to the occupational exposure of accelerator staff (up to 4% of $H^*(10)$). The mass of pions is equivalent to 273 electron masses and approximately 1/7 of a proton mass. Charged pions lose their energy mainly through Coulomb interactions. When negative pions come to rest they are usually captured by nuclei which then disintegrate emitting a variety of high-LET particles ('star fragmentation').

(B 122) Pelliccioni (1998) has carried out Monte Carlo calculations for evaluating mean quality factors averaged over the human body (see Eqn. B.3.12) for pions as a function of their energy. The results show that there is a moderate energy dependence of the mean quality factor for positive pions and for negative pions above 50 MeV (values between 1 and 2). Below this energy, the star fragmentation leads to an increase of q_E of negative pions.

(B 123) Considering that the energy distribution of pionsa in real radiation field is very broad and in view of their small contribution to total exposure in complex high-energy fields, it is recommended to use a weighting factor of 2 for all charged pions.

(B 124) ***Radiation weighting factor for alpha particles.*** Exposure of humans to alpha particles is predominantly from internal emitters, e.g., from inhaled radon progeny or ingested alpha-emitting radionuclides such as isotopes of plutonium, polonium, radium, thorium, and uranium. There are a number of epidemiological studies that provide information on the risk from inhaled or intravenously injected alpha emitters. The distribution of radionuclides and the estimation of dose and its

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distribution in tissues and organs are very complex and dependent on the models used. The dose distribution is generally very heterogeneous and the calculated doses are, therefore, associated with substantial uncertainties. For this reason epidemiological as well as experimental studies, although they can provide valuable guidance, cannot be used as the only basis for an assessment of the RBE for alpha emitters. From calculations using stopping power data for alpha particles in tissue and the $Q(L)$ function, the mean quality factor of 6 MeV alpha particles slowing down in tissues is estimated to be about 20.

(B 125) Reviews of available human and animal data on RBE for alpha-emitting radionuclides indicate that RBE depends on the biological end-point under consideration (UNSCEAR, 2000, Harrison and Muirhead, 2003). Variations between radionuclides in RBE values for the same end-point can be attributed mainly to differences in location of the emitter in tissue. The limited human data that allow estimation of alpha particle RBE values suggest values of around 10–20 for lung and liver cancer and lower values for bone cancer and leukaemia.

(B 126) There is good evidence, from animal and in-vitro studies, of RBE values for alpha emitters of around 10 or greater, compared with external low-LET radiations, for cancer-related effects. Studies of bone cancer induction in dogs suggest different RBE values for this endpoint for different bone-seeking alpha-emitting radionuclides, with high values for ^{239}Pu and low values for Ra isotopes (UNSCEAR, 2000). However, these comparisons are based on average skeletal doses, and the differences are most likely to be attributable to the different locations of the radionuclides in bone, with greater doses to target cells near to bone surfaces from ^{239}Pu and related actinide isotopes, which concentrate at bone surfaces, compared to isotopes of Ra which (as alkaline earth elements chemically similar to Ca) tend to be distributed more uniformly through the calcified bone matrix (ICRP, 1993c, Harrison and Muirhead, 2003). Human and animal data suggest that the RBE for the risk of leukaemia from alpha emitters deposited in bone is less than 20 (WHO, 2001, Harrison and Muirhead, 2003). The use of a w_R of 20 for alpha particles may thus lead to an overestimation of risk to target cells within active (red) bone marrow.

(B 127) Judgements on the available data and the selection of a w_R value for alpha particles have been reviewed in *Publication 92* (ICRP, 2003c). As recent data do not strongly support the need for a change of the radiation weighting factor for alpha particles, the w_R value of 20 is retained for these Recommendations (see Table B.4).

(B 128) ***Radiation weighting factor for heavy ions and fission fragments.*** Doses from fission fragments are of importance for radiological protection mainly in internal dosimetry, and the situation regarding radiation weighting factors may be seen as similar to that for alpha particles. Owing to their short ranges, the biokinetics and distribution of the actinides in the organs and tissues are very important and have a strong influence on their biological effectiveness. A radiation weighting factor of 20, as given in Tables B.3 and B.4, equal to that for alpha particles, may be regarded as a rough conservative estimate. The short range of the fission fragments in tissue and the high energy transferred, therefore, to a small volume of tissue results in a very high local dose at this point, which may reduce their RBE. As has been

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discussed in Section B.3.2, care must be taken when applying the concept of mean organ or tissue doses in such cases, and specific considerations are necessary.

(B 129) In external exposure heavy ions are mainly encountered in radiation fields near high energy accelerators, at aviation heights, and in space. Few RBE data for heavy ions are available and most are from in-vitro experiments. *Publication 92* (ICRP, 2003c) provides an overview on radiobiological data from which RBE values have been derived of relevance for defining radiation weighting factor values.

(B 130) RBE_M values of about 30 have been reported for induction of Harderian gland tumours in mice by the heavy ions ^{40}Ar and ^{56}Fe and lower values with radiation beams of lower LET (Fry et al., 1985, Alpen et al., 1993). The results indicate that RBE values reach a peak at about 100–200 keV μm^{-1} and remain at this level at higher LETs. RBE values for fission neutrons in the same system were shown to correspond to the maximum observed RBE value for heavy ions. In vitro studies of chromosome aberrations, cell transformation, and mutations also provide evidence of increasing RBE of heavy ions with increasing LET up to around 100–200 keV μm^{-1}, but suggest a decrease at very high LETs.

(B 131) Mean quality factors have been calculated by Sato et al. (2004). The radiation quality of the particle changes strongly along the track for heavy ions incident on a human body and stopped in the body. An averaged value may be chosen to derive a w_R. The selection of a single w_R value of 20 for all types and energies of heavy ions is judged to be appropriate for general application in radiological protection. For applications in space, where these particles contribute significantly to the total dose in the human body, a more realistic approach may be chosen based on the calculation of a mean quality factor in the human body as mentioned in Section B.3.5, paragraphs B 100 – B 115.

Tissue weighting factors

(B 132) The definition of effective dose takes into account the different relative radiosensitivities of the various organs and tissues in the human body with respect to radiation detriment from stochastic effects. For this purpose, weighting factors, w_T, were introduced in *Publication 26* (ICRP, 1977) for six identified tissues and for a remaining group of tissues (collectively referred to as the 'remainder'). In *Publication 60* (ICRP, 1991b) tissue weighting factors were specified for twelve tissues and organs and the 'remainder' (Table B.1). The tissue weighting factors are relative values, and their sum is equal to one so that a uniform dose distribution in the whole body gives an effective dose numerically equal to the equivalent dose in each organ and tissue of the body.

(B 133) The tissue weighting factors determined for these 2007 Recommendations are based on detriment-adjusted nominal risk coefficients for stochastic effects (Annex A). The unadjusted nominal risk coefficients are calculated by averaging estimates of the radiation-associated lifetime risk for cancer incidence for a composite population of equal numbers of males and females. The detriment is modelled as a function of life lost, lethality and loss of quality of life. With a few exceptions, the parameters in the risk models are estimated using cancer incidence data from

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the studies of the Japanese atomic bomb survivors. Both excess relative risk and excess absolute risk models are developed for most cancer sites.

(B 134) For heritable disease, the risk in the first two generations is taken into account as discussed and described in Annex A. The relative radiation detriments differ from those given in *Publication 60*, and this has resulted in changes to the w_T values. The main changes are for breast (from 0.05 to 0.12), gonads (from 0.20 to 0.08) and remainder tissues (from 0.05 to 0.12). In addition, specific w_T values of 0.01 are now given for the brain and salivary glands. The tissue weighting factors proposed by the Commission for the present Recommendations are given in Table B.2.

(B 135) The tissue weighting factors, w_T, are sex-averaged and are for the assessment of effective dose for workers as well as members of the public, including children. Recently the w_T values were also applied to the developing fetus in *Publication 88* (ICRP, 2001), although it was recognised that 'these w_T values have been developed for exposure of individuals after birth and that the apportionment of radiation detriment that these values imply may not be appropriate for doses received in utero'. The approach was, however, adopted in the absence of comprehensive data on the relative risks to organs and tissues from exposures in utero. It was concluded in *Publication 90* (ICRP, 2003a) and by Streffer (2005) that there are at present insufficient data to be able to make recommendations of specific w_T values for prenatal radiation exposures.

(B 136) In the case of sex-specific differences in relative detriment based on cancer incidence for the ovaries of females (Annex A, Section A.4.6) the sex-averaged w_T of 0.08 assigned to the gonads (cancer plus heritable effects) is similar to that of the female ovaries (0.036) plus heritable effects (0.039). In this way the ovary of females is judged to be sufficiently protected.

(B 137) In the case of the thyroid, the values of the relative detriment based on cancer incidence for females (0.021) and males (0.008) (Annex A, Section A.4.6) differ by a factor of almost 3. However, since the w_T assigned to the thyroid is given as 0.04 to allow for the high susceptibility of young children, the difference in detriment between the sexes is considered in a conservative manner.

(B 138) A particular issue in the calculation of effective dose is the assessment of the dose to 'remainder' tissues. In *Publication 26* (ICRP, 1977), the remainder tissue was assigned a weighting factor of 0.30. The dose equivalent to the remainder tissues was taken to be the arithmetic average of the dose to the five most highly irradiated tissues of the remainder by allocating a w_T value of 0.06 to each of these tissues. This procedure resulted in a lack of additivity of the effective dose equivalent quantity, since the five tissues could vary for different exposures, either external or internal.

(B 139) In *Publication 60*, the remainder tissue was given a weighting factor of 0.05. However, additivity was still lacking although reduced in magnitude owing to the splitting rule given in Note 3 of Table A-3 in *Publication 60* (see below). The equivalent dose for the remainder was given as the mean value for ten specified tissues and organs (Table B.1). The upper large intestine, formerly included in the remainder (ICRP, 1991b), was taken together with the lower large intestine, to define the colon (ICRP, 1995a). *Publication 66* (ICRP, 1994a) dealing with doses to the

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respiratory tract and dose coefficients for inhaled radionuclides specified that the extrathoracic airways be considered as part of the remainder.

(B 140) While not detailed in *Publication 60* (ICRP, 1991b), the treatment of remainder was described in *Publications 68* and *72* (ICRP, 1994b, 1996c). The remainder dose was defined by the mass-weighted average of the equivalent dose to organs and tissues of the remainder (Note 2 of Table A-3 in *Publication 60*). Owing to the very different masses the contribution of the specified tissues and organs to the remainder dose was very different. Because of its large mass, muscle received an effective weighting factor of nearly 0.05 which is not justified because its radiation sensitivity is judged to be low. For external exposure, however, the dose to the various tissues are similar (differ little from that of muscle) and hence in *Publication 74* (ICRP, 1996b) a simple arithmetic dose averaging with no further weighting was used as an approximation (see Section B.3.4).

(B 141) The method for calculating effective dose recommended in *Publication 60* (ICRP, 1991b) includes provision for cases when a remainder tissue which does not have an explicit weighting factor (w_T) receives the highest dose of all tissues. In these cases the w_T for remainder (0.05) is divided equally between the mass-weighted average dose to remainder tissues (i.e., the default remainder dose, see above) and the particular tissue. This is often referred to as the 'splitting rule' and cases where the rule applies are known as 'split remainder' cases.

(B 142) Implications of this rule were explored by Nelson et al. (1997). The intention of the splitting rule was to provide protection, through the effective dose and its related limits, to potentially highly exposed tissues (such as extrathoracic region, ET_1 or the kidney after incorporation of certain radionuclides) which had not been assigned a specific weighting factor. One of the drawbacks of this approach, however, is that, since the formulation of the effective dose can differ for different radionuclides or for different external photon beam energies, it is not strictly an additive quantity.

(B 143) It is now recommended that the equivalent doses to the specified tissues of the remainder given in Table B.2 are added with no further mass weighting. This means that the weighting factor given to each of the remainder tissues is smaller than the least value assigned to any of the named tissues (0.01). For remainder tissues the w_T is 0.12.

(B 144) In its computations, the Commission assigns a dose to the remainder which represents the arithmetic average of the doses to the remainder tissues of both sexes. Analogous to the approach for other organs and tissues, the equivalent dose to the remainder is defined separately for males and females, and these values are included into Eqn. (B.3.9). The equivalent dose to the remainder tissues is computed as the arithmetic mean of the equivalent doses to the tissues listed in the footnotes to Table B.2. The current remainder formulation specifies 12 tissues common to both sexes and one sex-specific tissue in each sex (prostate in the male and uterus/cervix in the female) for a total of 13 tissues. The equivalent dose to the tissues of remainder of the male, H^{M}_{rem}, and female, H^{F}_{rem}, are computed as:

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$$H_{\mathrm{rem}}^{\mathrm{M}} = \frac{1}{13}\sum_{\mathrm{T}}^{13} H_{\mathrm{T}}^{\mathrm{M}} \text{ and } H_{\mathrm{rem}}^{\mathrm{F}} = \frac{1}{13}\sum_{\mathrm{T}}^{13} H_{\mathrm{T}}^{\mathrm{F}}. \tag{B.3.17}$$

(B 145) The summation in Eqn. (B.3.9) extends over the equivalent dose to remainder tissues in the male and female.

B.3.6. References, Section B.3

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B.4. Operational quantities

(B 146) The body-related protection quantities (equivalent dose and effective dose) are not measurable in practice and therefore cannot be used directly as quantities in radiation monitoring. Operational quantities are, therefore, used for the assessment of effective dose or equivalent doses in tissues or organs (Figs B.1 and B.2).

(B 147) Operational quantities are aimed at providing an estimate or upper limit for the value of the protection quantities related to an exposure, or potential exposure of persons under most irradiation conditions. They are often used in practical regulations or guidance. As shown in Fig. B.2, different types of operational quantities are used for internal and external exposures. For monitoring of external radiation exposures operational dose quantities have been defined by ICRU (ICRU, 1985, 1988), see Section B.4.2, and, during the 1990s, introduced into radiological protection practice in many countries. Their further use is recommended, and only small changes are proposed. In internal dosimetry, no operational dose quantities have been defined which directly provide an assessment of equivalent or effective dose. Different methods are applied to assess the equivalent or effective dose due to radionuclides in the human body. They are mostly based on various activity measurements and the application of biokinetic models (computational models) (see Section B.4.2).

B.4.1. External exposure

(B 148) Specific operational dose equivalent quantities are defined for radiation monitoring in situations of external exposure (area or individual monitoring). In routine monitoring, the values of these dose-equivalent quantities are taken as sufficiently precise assessments of effective dose or skin dose, respectively, especially if their values are below the protection limits.

(B 149) Operational dose quantities are used for monitoring external exposures because:

- point quantities are needed for area monitoring;
- in area monitoring, the value of the dose quantity should not depend on the directional distribution of the incident radiation;
- instruments for radiation monitoring need to be calibrated in terms of a physical quantity for which calibration standards exist.

(B 150) Different operational dose equivalent quantities have been defined for area and individual monitoring.

(B 151) The basic concept of the operational dose quantities for external exposure is described in ICRU Reports 39 and 43 (ICRU, 1985, 1988). The definitions adopted for the 2007 Recommendations are given in ICRU Report 51 (ICRU, 1993b) and in ICRU Report 66 (ICRU, 2001b).

(B 152) As described in Section B.1, the quantity dose equivalent, H, is defined by

$$H = Q \cdot D \tag{B.4.1}$$

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where D is the absorbed dose at the point of interest in tissue and Q the corresponding quality factor at this point, the value of which is determined by the type and energy of charged particles passing a small volume element at this point. It is well known that the biological effectiveness of a radiation is correlated with the ionisation density along the track of charged particles in tissue. Therefore, Q is defined as a function of the unrestricted linear energy transfer, L_∞ (often denoted as L or LET), of charged particles in water:

$$Q(L) = \begin{cases} 1 & L < 10\ \text{keV}/\mu\text{m} \\ 0.32\,L - 2.2 & 10 \leqslant L \leqslant 100\ \text{keV}/\mu\text{m} \\ 300/\sqrt{L} & L > 100\ \text{keV}/\mu\text{m} \end{cases} \tag{B.4.2}$$

(B 153) The quality factor function $Q(L)$ was given in *Publication 60* (ICRP, 1991b). The function is the outcome of judgements taking account of results of radiobiological investigations on cellular and molecular systems as well as on the results of animal experiments. The radiobiological database for the assessment of this function is largely unchanged since 1990 (see ICRP, 2003c) and no changes are proposed.

(B 154) The quality factor Q at a point in tissue is then given by:

$$Q = \frac{1}{D}\int_{L=0}^{\infty} Q(L) D_L \mathrm{d}L \tag{B.4.3}$$

where $D_L = \frac{\mathrm{d}D}{\mathrm{d}L}$ is the distribution of D in L for the charged particles contributing to absorbed dose at the point of interest. This function is particularly important for neutrons because various types of secondary charged particles are produced in tissue by neutron interactions.

(B 155) Different operational dose quantities are required for different tasks in radiological protection. These include area monitoring for controlling the radiation in workplaces and for defining controlled or restricted areas, and individual monitoring for the control and limitation of individual exposures. While measurements with an area monitor are preferably performed free in air, personal dosimeters are worn on the body. As a consequence, in a given situation, the radiation field 'seen' by an area monitor free in air differs from that 'seen' by a personal dosimeter worn on the body where the radiation field is strongly influenced by the backscatter and absorption of radiation in the body. The use of different operational dose quantities reflects these differences.

(B 156) Table B.5 can be used in order to describe the application of the different operational dose quantities for the different tasks of monitoring of external exposures.

(B 157) Using the scheme of Table B.5, it is not necessary to use the terms 'strongly penetrating radiation' (also called 'penetrating radiation') and 'low-penetrating radiation' (also called 'weakly penetrating radiation') in specifying the range of application of the operational quantities. ICRU (1993b) stated that $H^*(10)$ and $H_\mathrm{p}(10)$ are designed for monitoring strongly penetrating radiation, e.g., photons (above about 12 keV) and neutrons, while $H'(0.07, \Omega)$ and $H_\mathrm{p}(0.07)$ are applied for monitoring low-penetrating radiation, e.g., beta particles. Furthermore, $H_\mathrm{p}(0.07)$ is also used

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Table B.5. Application of operational dose quantities for monitoring of external exposures.

Task	Operational dose quantities for	
	area monitoring	individual monitoring
Control of effective dose	ambient dose equivalent, $H^*(10)$	personal dose equivalent, $H_p(10)$
Control of doses to the skin, the hands and feet and the lens of the eye	directional dose equivalent, $H'(0.07,\Omega)$	personal dose equivalent, $H_p(0.07)$

for monitoring the doses to the hands and feet from all ionising radiation. The rarely used quantities $H'(3, \Omega)$ and $H_p(3)$ for monitoring the exposure of the lens of the eye are not included in this scheme. Monitoring of $H_p(0.07)$ can be used for the same monitoring purpose (see also this Section, paragraphs B 165 – B 167).

(B 158) There are situations in which individual monitoring is not used and where area monitoring or computational methods are applied to assess individual exposures. These situations include the assessment of doses to aircrew, prospective dose assessments and assessment of doses in workplaces and the natural environment.

Operational quantities for area monitoring

(B 159) For all types of external radiation, the operational quantities for area monitoring are defined on the basis of a dose equivalent value at a point in a simple phantom, the ICRU sphere. It is a sphere of tissue-equivalent material (30 cm in diameter, ICRU (soft) tissue with density: 1 g cm^{-3}, and mass composition: 76.2% oxygen, 11.1% carbon, 10.1% hydrogen, and 2.6% nitrogen). For radiation monitoring, in most cases it adequately approximates the human body as regards the scattering and attenuation of the radiation fields under consideration.

(B 160) The operational quantities for area monitoring defined in the ICRU sphere should retain their character of a point quantity and the property of additivity. This is achieved by introducing the terms 'expanded' and 'aligned' radiation field in the definition of these quantities.

(B 161) An *expanded* radiation field, defined as a hypothetical field, is a radiation field in which the spectral and the angular fluence have the same value in all points of a sufficiently large volume equal to the value in the actual field at the point of interest. The expansion of the radiation field ensures that the whole ICRU sphere is thought to be exposed to a homogeneous radiation field with the same fluence, energy distribution and direction distribution as in the point of interest of the real radiation field.

(B 162) If all radiation is aligned in the expanded radiation field so that it is opposed to a radius vector Ω specified for the ICRU sphere, the *aligned and expanded* radiation field is obtained. In this hypothetical radiation field, the ICRU sphere is homogeneously irradiated from one direction, and the fluence of the field is the integral of the angular differential fluence at the point of interest in the real radiation field over all directions. In the expanded and aligned radiation field, the value of

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the dose equivalent at any point in the ICRU sphere is independent of the direction distribution of the radiation in the real radiation field. Conversion coefficients relating radiation field quantities to the operational quantities are usually calculated assuming a vacuum outside of the phantom considered.

(B 163) ***Ambient dose equivalent, $H^*(10)$***. For area monitoring the operational quantity for assessing effective dose is the ambient dose equivalent, $H^*(10)$, defined by (ICRU, 2001b):

- The *ambient dose equivalent*, $H^*(10)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of 10 mm on the radius vector opposing the direction of the aligned field.

(B 164) In most practical situations of external radiation exposure, the ambient dose equivalent fulfils the aim of providing a conservative estimate or upper limit for the value of the limiting quantities. This is not always the case for persons in high energy radiation fields such as in the vicinity of high energy accelerators and in cosmic ray fields (Pelliccioni, 1998). The depth at which secondary charged particle equilibrium is achieved is very important in these cases. For very high energy particles a depth of 10 mm in ICRU tissue, as defined with the operational quantities, is not sufficient to complete the charged particle build-up in front of that point and hence the operational quantities will underestimate effective dose. In radiation fields relevant for aircrew exposure, however, $H^*(10)$ appears to be an appropriate operational quantity if the recommended radiation weighting factors for neutrons and protons (see Section 3.5, paragraphs B 100 – B 123) are considered (Pelliccioni, personal communication).

(B 165) ***Directional dose equivalent, $H'(d,\Omega)$***. For area monitoring of low-penetrating radiation, the operational quantity is the directional dose equivalent, $H'(0.07, \Omega)$ or, in rare cases, $H'(3, \Omega)$ defined as follows:

- The *directional dose equivalent*, $H'(d, \Omega)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth, d, on a radius in a specified direction Ω.
- For low-penetrating radiation it is $d = 0.07$ mm, and $H'(d, \Omega)$ is then written $H'(0.07, \Omega)$.

(B 166) In the case of monitoring the dose to the lens of the eye, $H'(3, \Omega)$ with $d = 3$ mm was recommended by ICRU. The quantities directional dose equivalent, $H'(3, \Omega)$, and personal dose equivalent $H_p(3)$, however, have rarely been used in practice and very few instruments exist for measuring these quantities. It is suggested that their use is discontinued because the monitoring of the exposure to the eye lens is also sufficiently achieved if the dose to the eye lens is assessed in terms of the other operational quantities. $H_p(0.07)$ is normally used for this special purpose (ICRU 1998).

(B 167) For area monitoring of low-penetrating radiation, $H'(0.07, \Omega)$ is almost exclusively used. With unidirectional radiation incidence, mainly occurring in calibration procedures, the quantity may be written $H'(0.07,\alpha)$, where α is the angle

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between the direction Ω and the direction opposite to radiation incidence. In radiological protection practice the direction Ω is often not specified, because it is mostly the maximum value of $H'(0.07, \Omega)$ at the point of interest which is of importance. It is usually obtained by rotating the dose rate meter during the measurement and looking for the maximum reading.

Operational quantities for individual monitoring

(B 168) Individual monitoring of external exposure is usually performed with personal dosimeters worn on the body, and the operational quantity defined for this application takes this situation into account. The true value of the operational quantity is determined by the irradiation situation near the point where the dosimeter is worn. The operational quantity for individual monitoring is the personal dose equivalent, $H_p(d)$.

(B 169) The *personal dose equivalent*, $H_p(d)$, is the dose equivalent in ICRU (soft) tissue at an appropriate depth, d, below a specified point on the human body. The specified point is usually given by the position where the individual dosimeter is worn. For the assessment of effective dose a depth $d = 10$ mm is recommended, and for assessing equivalent dose to the skin, and to the hands and feet, a depth $d = 0.07$ mm. In special cases of monitoring the dose to the lens of the eye, it has been proposed that a depth $d = 3$ mm would be appropriate (cf. paragraph B 166).

(B 170) An operational quantity for individual monitoring should allow the effective dose to be assessed or should provide a conservative estimate under nearly all irradiation conditions. This, however, requires that the personal dosimeter be worn at a position on the body which is representative with respect to the exposure. For a dosimeter position in front of the trunk, the quantity $H_p(10)$ mostly furnishes a conservative estimate of E even in cases of lateral or isotropic radiation incidence on the body. In cases of exposure from the back only, however, a dosimeter worn at the front side and correctly measuring $H_p(10)$, will not appropriately assess E. Also in cases of partial body exposures the reading of a personal dosimeter may not provide a representative value for the assessment of effective dose.

B.4.2. Internal exposure

(B 171) The system of dose assessment for intakes of radionuclides that is generally applied relies first on the calculation of the intake of a radionuclide either from direct measurements (e.g., measuring the radioactivity of the whole body by whole body counter or of specific organs and tissues by external counting devices) or indirect measurements (e.g., measuring the radioactivity in urine, faeces, air or other environmental samples). Biokinetic models have to be applied and the effective dose is calculated from the intake using reference dose coefficients (doses per unit intake, Sv Bq^{-1}) recommended by the Commission, and also reproduced in the EU Basic Safety Standards Directive (EU, 1996) and in the International Basic Safety Standards (IAEA, 1996). The Commission has provided dose coefficients for intakes by inhalation and ingestion for a large number of radionuclides, relating the intake of a specific radionuclide to the corresponding organ and effective dose committed

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within a specified period (ICRP, 1994b, 1996c). Dose coefficients have been given for members of the public and for adults who are occupationally exposed.

(B 172) A paper by Berkovski et al. (2003) indicated that an alternative approach may be more useful in some circumstances. There can be advantages in calculating the committed effective dose *directly* from the measurements using functions that relate them to the time of the intake. The measurements could be the whole body or organ content, urine or faecal sample, or even an environmental measurement. This approach would require that the Commission provides additional tables of 'dose per unit content' as a function of time after the intake for interpreting the measurement data, but this approach should facilitate the interpretation of monitoring data in many circumstances. It aids the analysis by ensuring that current models are used in the dose assessment and limits the opportunity to make errors by reading data from tables.

B.4.3. References, Section B.4

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B.5. Practical application of dose quantities in radiological protection

(B 173) The main areas of application of dose quantities in radiological protection of both occupational workers and the general public to exposures from controlled sources are as follows:

- prospective dose assessment for planning and optimisation of protection; and
- retrospective dose assessment for demonstrating compliance with dose limits.

(B 174) In practice, limits, constraints, reference values, and action levels are defined in terms of dose quantities in order to restrict the risks from radiation exposure for both occupational workers and the public. The primary dose limits in radiological protection are given in terms of equivalent dose or effective dose. Since neither quantity can be directly measured, as has been explained above, they are assessed using other measurable quantities, models and computations (Figs. B.1 and B.2). Depending on the situation considered (occupational or public exposure), different procedures are applied.

B.5.1. Radioactivity and committed dose

(B 175) Calculations of the radiation dose from internal or external exposure to radiation emitted from radionuclides require information on their half-life and the type, energies, and intensities of the nuclear and atomic radiations emitted by the radionuclide. The data of *Publication 38* (ICRP, 1983b) are the same as have been used in ICRP publications since 1980. The strategy for preparing a database of nuclear decay data to replace *Publication 38* has been outlined by Endo et al. (2003, 2005). This database will be used in future calculations of dose coefficients.

(B 176) The activity A of an amount of a radionuclide in a particular energy state at a given time is the quotient of $\mathrm{d}N$ by $\mathrm{d}t$, where $\mathrm{d}N$ is the expectation value of the number of spontaneous nuclear transitions from that energy state in the time interval $\mathrm{d}t$, that is:

$$A = -\frac{\mathrm{d}N}{\mathrm{d}t} \tag{B.5.1}$$

The SI unit of activity is s^{-1} with the special name becquerel (Bq), 1 Bq = 1 s^{-1}

(B 177) Radionuclides are frequently included in or absorbed onto other solid, liquid, or gaseous material as well as being accompanied by stable isotopes of the same element, and the amount is defined by further quantities.

(B 178) The *specific activity* a_m (also called *massic activity* or *activity divided by mass* or *activity per mass*) of a specified radionuclide in a sample is the activity A of the radionuclide in the sample divided by the total mass m of the sample.

(B 179) The *activity concentration* a_v (also called *volumic activity* or *activity divided by volume* or *activity per volume*) of a specified radionuclide in a volume is the activity A of the radionuclide in the volume divided by the volume V.

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(B 180) The *surface activity concentration* a_F (also called *areal activity concentration* or *aeric activity*) of a specified radionuclide on a surface is the activity A of the radionuclide on the surface area F divided by the area.

(B 181) The names and symbols of these three quantities have not been consistently standardised and there are some differences between the definitions used by different international bodies, including ICRU (ICRU, 2001b), ISO (ISO, 1992), IEC (IEC 2005), and ICRP. Harmonisation would be very helpful to avoid errors and inconsistencies.

(B 182) The activity intake, I, is the amount of the specified radionuclide entering the human body by ingestion, inhalation, or absorption through the skin. This intake is often used as an operational quantity for the assessment of effective dose. In general, it cannot be measured directly, and must be determined from other data such as whole or partial body measurements, assessments of activity in excreta or environmental measurements such as air samples (Fig. B.1). In the case of accidents, activity may also enter the body through wounds. A model to describe entry into the body through wounds, and subsequent uptake to blood, has been described by NCRP (2006).

(B 183) Radionuclides incorporated in the human body irradiate tissues over time periods determined both by their physical half-life and their biological retention within the body. Thus they may give rise to doses to body tissues over very short periods or throughout life. For example, in the case of intakes of tritiated water, because of its short biological half-time of retention (10 days; physical half-life of 12.3 yr), essentially all the dose is delivered within 2–3 months after intake. For ^{239}Pu, however, both biological retention times and the physical half-life (24,000 yr) are very long, and dose will be accumulated over the remaining lifespan of the individual. Thus, for inhalation of ^{239}Pu as plutonium nitrate (a Type M form in the Human Respiratory Tract Model, HRTM, ICRP, 1994a) models predict that only about 10% of the committed effective dose is received within the first year and about 30% by the end of 10 years. These and other examples are shown in Fig. B.5. The figure also shows the different rates of accumulation of committed equivalent doses to different tissues after inhalation of insoluble thorium–232 (Type S).

(B 184) The need to regulate exposures to radionuclides and the accumulation of radiation dose over extended periods of time led to the definition of committed dose quantities. The committed dose from an incorporated radionuclide is the total dose expected to be delivered within a specified time period. The *committed equivalent dose*, $H_T(\tau)$, in a tissue or organ T is defined by

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t) \tag{B.5.2}$$

where τ is the integration time following the intake at time t_0. The quantity *committed effective dose*, $E(\tau)$, is then given by

$$E(\tau) = \sum_T w_T H_T(\tau) \tag{B.5.3}$$

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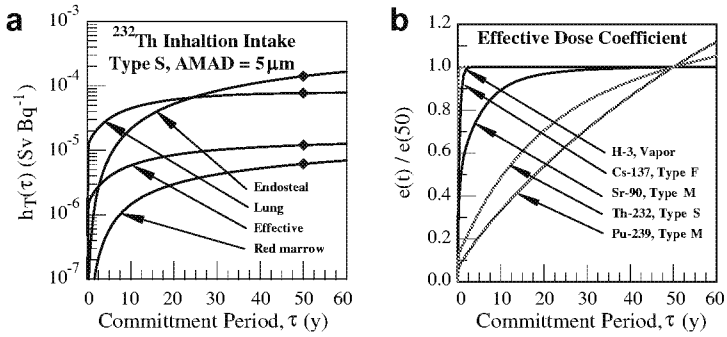

Fig. B.5. The committed dose coefficients as a function of integration period. (a) Committed equivalent dose coefficients in endosteal tissue, lung, and active (red) bone marrow, and committed effective dose coefficient as a function of integration time (τ) following inhalation intake of ^{232}Th. Points mark the 50 year period. (b) Committed effective dose coefficient for selected radionuclides normalised to their value at 50 y.

The Commission continues to recommend that, for compliance with dose limits and management of staff, the committed dose is assigned to the year in which the intake occurred.

(B 185) For workers, the committed dose is normally evaluated over the 50-year period following the intake. The commitment period of 50 years is a rounded value considered by the Commission to be the life expectancy of a young person entering the workforce. The committed effective dose from intakes is also used in prospective dose estimates for members of the public. In these cases a commitment period of 50 years is considered for adults. For infants and children the dose is evaluated to age 70 years (ICRP, 1996c).

B.5.2. Reference phantoms

(B 186) Effective dose is defined for the sex-averaged Reference Person (Section B.3.4). To determine effective dose, first the equivalent doses in the organs and tissues of the reference male and the reference female have to be evaluated and then averaged in order to obtain the equivalent doses of the Reference Person. Effective dose is obtained by multiplying these with sex-averaged tissue weighting factors and summing over all tissue weighted equivalent doses of the Reference Person (Eqn. B.3.7; Fig. B.3).

(B 187) The evaluation of equivalent doses for the Reference Male and Female, and of effective dose for the Reference Person, is based on the use of anthropomorphic models. In the past, the Commission did not specify a particular phantom and, in fact, various mathematical phantoms such as hermaphrodite MIRD-type phantoms, the sex-specific models of Kramer et al. (1982) or the age-specific phantoms of Cristy and Eckerman (1987) have been used.

(B 188) The Commission has now adopted male and female reference phantoms for the calculation of equivalent doses for organs and tissues. In order to provide

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a practicable approach for the assessment of equivalent doses and effective dose, conversion coefficients relating to physical quantities, e.g., particle fluence or air kerma for external exposure, and activity intake for internal exposure, are calculated for standard exposure conditions of the reference phantoms (mono-energetic radiations, standard geometries for external irradiations, standard biokinetics of radionuclides in the human body, etc.).

(B 189) Voxel (voxel: volume element) models, constructed from medical image data of real persons, give a more realistic description of the human body than the mathematical, stylised phantoms. Thus, the Commission decided to use voxel models to define its reference phantoms to be used for the update of organ dose conversion coefficients. These models (or computational phantoms) represent the Reference Male and Female, and have organ masses in compliance to the reference values, compiled in *Publication 89* (ICRP, 2002).

(B 190) Two voxel reference models of an adult male and an adult female have been developed (Zankl et al., 2005, Zankl et al., 2007), based on voxel models of two individuals whose body height and weight were close to those of the Reference Male and Female. They were developed from computed tomographic images obtained from high resolution continuous scans of a single individual and consist of millions of voxels, providing a three-dimensional representation of the human body and the spatial form of its constituent organs and structures. Approximately 140 organs and tissues were defined, including different skeletal tissues, cartilage, muscle and the main blood vessels. The organ masses of both models were adjusted to approximate those assigned to the Reference Adult Male and Female in *Publication 89* (ICRP, 2002) without distorting the realistic anatomy.

(B 191) The voxel reference models are thus computational representations of Reference Male and Female and can be used, together with codes simulating the radiation transport and energy deposition, for the computation of dose coefficients for workers and adult members of the public for internal exposure. The models can be used to compute the fraction of the energy of radiation emitted within source region S_i that is absorbed in target region T_j. Similarly the models will be used to compute the mean absorbed dose, D_T, in an organ or tissue T, from radiation fields external to the body, and the relationship of the effective dose to the quantities specific to the radiation field. Reference computational phantoms for children of different ages will also be developed for use in the calculation of dose coefficients for members of the public.

B.5.3. Committed effective dose coefficients for internal exposure

(B 192) In the occupational setting, each intake of a radionuclide during a year is assigned a committed effective dose, $E(\tau)$, where a commitment period τ of 50 years is considered for workers. The same period is chosen for adult members of the public, while for infants and children the dose rate is integrated up to the age of 70 years (ICRP, 1996c).

(B 193) Committed effective dose coefficients, $e(\tau)$, are conversion coefficients for a Reference Person which provide numerical links between $E(\tau)$ and measurable quan-

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tities, in this case between $E(\tau)$ and the intake of radionuclide(s) by either inhalation (e_{inh}) or ingestion (e_{ing}) of radionuclides. The dose coefficients for the female and male are based on the sex-specific physiological, anatomical, and biokinetic parameters of the reference adult females and males. In addition, the dosimetric parameters in the evaluation of the mean absorbed dose in tissue T are derived for sex-specific computational phantoms (see Section B.5.2).

(B 194) The contribution of the remainder tissue to the effective dose is derived by applying the tissue weighting factor for this group of tissues to the arithmetic average equivalent dose among tissues not assigned an explicit tissue weighting but listed as remainder tissues (see Section B.3.5, paragraphs B 132 – B 145). The dose to remainder tissues is evaluated in a manner that provides for additivity of the effective dose.

(B 195) Thus, committed effective dose coefficients based on the sex and population-averaged tissue weighting factors given in Table B.2, should be computed as

$$e(\tau) = \sum_{\mathrm{T}} w_{\mathrm{T}} \left[\frac{h_{\mathrm{T}}^{\mathrm{M}}(\tau) + h_{\mathrm{T}}^{\mathrm{F}}(\tau)}{2} \right] \tag{B.5.4}$$

where $h_{\mathrm{T}}^{\mathrm{M}}(\tau)$ and $h_{\mathrm{T}}^{\mathrm{F}}(\tau)$ are the committed equivalent dose coefficients for tissue T of the Reference Male and Reference Female, respectively (Fig. B.3). An analogous equation is applicable to external exposures.

B.5.4. Conversion coefficients for external exposure

(B 196) As described in Section B.4 the protection quantities, equivalent dose and effective dose, are not measurable, and their values are assessed using their relationship to either physical radiation field quantities, e.g., air kerma free in air, K_{a}, or particle fluence, ϕ, or operational dose quantities. Conversion coefficients defined for a reference person provide numerical links between these quantities, and it is very important that an internationally agreed set of conversion coefficients is available for general use in radiological protection practice for occupational exposures and exposures of the public.

(B 197) Based on the work of a joint ICRU/ICRP task group, the Commissions published reports (ICRP, 1996b, ICRU, 1997) on 'Conversion coefficients for use in radiological protection against external radiation' which recommended a set of evaluated data of conversion coefficients for protection, and operational quantities for external exposure to mono-energetic photon, neutron, and electron radiation under specific irradiation conditions. Most of the data for protection quantities used for the evaluation were calculated on the basis of MIRD-like models of the anatomy. In all cases, whole body exposure was assumed. For photons the mean absorbed dose in an organ or tissue per air kerma free in air and the effective dose per air kerma free in air are given, while for neutrons and electrons the doses are related to the particle fluence. Furthermore, *Publication 74* (ICRP, 1996b) explored in detail the relationship between the protection quantity effective dose and the operational dose quantities for specific idealised irradiation exposure geometries. Partial body

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exposures were not discussed in that publication, and recommended conversion coefficients are not available for these cases.

(B 198) The definition of new reference phantoms for the human body (male and female voxel phantoms based on medical imaging data) requires the calculation of a new set of conversion coefficients for all types of radiation and irradiation geometries considered. For most organs, however, the differences from the existing data of $D_{T,R}$ (ICRP, 1996b) are likely to be moderate. The values of the coefficients for effective dose are also dependent on w_R and w_T values, and their changes may have a larger influence on the changes in conversion coefficients, especially for neutrons and protons.

(B 199) The adoption of voxel-based reference phantoms (ICRP, 2002) requires new calculations of conversion coefficients for all radiations and irradiation geometries of interest which will replace the existing data sets (ICRP, 1996b). Calculations for photons have shown that the changes in the values of effective dose for photon radiation are generally small (Zankl et al., 2002). At low photon energy, however, the change in exterior shape of the body and hence the depth of an organ in the reference phantoms can influence the absorbed dose, e.g., for the thyroid. The resultant change in the effective dose coefficients is expected to be rather modest (Schlattl et al., 2007).

B.5.5. Occupational exposure

(B 200) In cases of occupational exposure, doses may arise from external and internal radiation sources. For external exposure individual dose monitoring is usually performed by measuring the personal dose equivalent $H_p(10)$ using a personal dosimeter and taking this measured value as an acceptable assessment of the value of effective dose under the assumption of a uniform whole-body exposure. For internal exposure committed effective doses are determined based on assessment of intakes of radionuclides from bioassay measurements or other quantities (e.g., activity retained in the body or in daily excreta – in exceptional cases the airborne activity concentration can be used) and the application of appropriate dose coefficients.

(B 201) For practical purposes the values from both kinds of quantities should be combined in the assessment of the value of total effective dose for demonstrating compliance with dose limits and constraints.

(B 202) In most situations of occupational exposure the effective dose, E, can be derived from operational quantities using the following formula:

$$E \cong H_p(10) + E(50) \tag{B.5.5}$$

where $H_p(10)$ is the personal dose equivalent from external exposure (see Section B.4.4) and $E(50)$ the committed effective dose from internal exposure.

(B 203) For the assessment of effective dose from external exposure, according to Eqn. (B.5.5) by monitoring the exposure with a personal dosimeter measuring $H_p(10)$ it is necessary that the personal dosimeter is worn at a position on the body which is representative of the exposure of the body. If the measured dose value is well below the annual dose limit, the value of $H_p(10)$ is usually taken as a sufficient

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estimate of effective dose. For high personal doses approaching or exceeding the annual dose limit, or in strongly inhomogeneous radiation fields, however, this procedure might not be sufficient and it would then be necessary to carefully consider the actual situation of exposure in the human body in assessing the effective dose. The use of personal protective equipment (PPE) and other protection measures may also need to be taken into account.

(B 204) In the special case of exposure of aircrew to cosmic radiation, individual monitoring with personal dosimeters, measuring $H_p(10)$, is usually not performed for the assessment of effective dose. There may be other working environments in which personal dosimeters are not used. In these cases the effective dose from external exposure can be assessed from monitoring ambient dose equivalent, $H^*(10)$, or by calculation using radiation field properties.

(B 205) In cases of external exposure to low-penetrating radiation, e.g., β-rays, $H_p(10)$ will not sufficiently assess effective dose. In such cases $H_p(0.07)$ may be used to assess the equivalent dose to the skin and its contribution to effective dose by applying the tissue weighting factor of 0.01 for the skin.

(B 206) The new computational phantoms will be used to compute the equivalent dose in tissue T, H_T, from radiation fields external to the body and the relationship of the effective dose to the operational quantities specific to the radiation field. Conversion coefficients representing the effective dose per unit fluence or air kerma as a function of radiation energy need to be calculated for various irradiation geometries and will be applicable to external exposures at the workplace. The same reference computational phantoms will also be used to derive dose coefficients for equivalent dose, H_T in relevant target regions as well as for effective dose.

(B 207) In cases of external exposure to beta particles, very inhomogeneous irradiation of the body will occur. Even at effective doses below the limits high local skin doses could occur where tissue reactions are possible. For this reason the annual limit on skin dose (500 mSv for occupational exposure) corresponds to the local skin dose defined by the mean equivalent dose in 0.07mm depth averaged over any 1 cm^2 of the skin.

(B 208) The committed effective dose, $E(50)$, from intakes of radionuclides is assessed by:

$$E(50) = \sum_j e_{j,inh}(50) \cdot I_{j,inh} + \sum_j e_{j,ing}(50) \cdot I_{j,ing} \qquad \text{(B.5.6)}$$

where $e_{j,inh}(50)$ is the committed effective dose coefficient for activity intakes by inhalation of a radionuclide j, $I_{j,inh}$ is the activity intake of a radionuclide j by inhalation, $e_{j,ing}(50)$ is the committed effective dose coefficient for activity intakes of a radionuclide j by ingestion, and $I_{j,ing}$ is the activity intake of a radionuclide j by ingestion. In the calculation of the effective dose from specific radionuclides, allowance will need to be made for the characteristics of the material taken into the body.

(B 209) The dose coefficients used in Eqn. (B.5.6) are those specified by the Commission with no departure in anatomical, physiological, and biokinetic characteristics from those of the Reference Male and Reference Female (ICRP, 2002). Account may, however, be taken of the activity medium aerodynamic diameter

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(AMAD) of the inhaled aerosol, and the chemical form of the particulate matter to which the specified radionuclide is attached. The effective dose assigned in the worker's dose record, the 'dose of record', is that value of effective dose which the Reference Person would experience owing to the radiation fields and activity intakes encountered by the worker (see Section 5.8). The commitment period of 50 years relates to the life expectancy of a person entering the workforce, as noted in Section B.5.1.

(B 210) The radiation dose from radon isotopes and their decay products may also need to be taken into account in the overall dose assessment (ICRP, 1993b). If incorporation of radionuclides through the skin occurs, an additional term for the associated effective dose would have to be included in Eqn. (B.5.6). The incorporation of radionuclides through uncontrolled events involving wounds has implications beyond compliance with work practices, and thus these events are not included in Eqn. (B.5.6). The significance of these events must be evaluated and recorded, appropriate medical treatment provided, and further restriction of the worker's exposure considered if warranted.

(B 211) Exposure to airborne noble gas radionuclides in the workplace may need to be assessed beyond that indicated by $H_p(10)$. In such cases it is necessary to include in Eqn. (B.5.6) a term representing the product of the time-integrated airborne concentration of the noble gas and an effective dose coefficient for so-called submersion exposure. Such dose coefficients are specified by the Commission for both prospective and retrospective applications.

(B 212) In the assessment of committed effective doses for workers from operational data related to an actual intake of specific radionuclide(s) or of radionuclide concentration(s) in the air at a workplace it is often useful to refer these data to the Annual Limit on Intake (ALI) and the Derived Air Concentration (DAC).

(B 213) The ALI was defined in *Publication 60* (ICRP, 1991b, paragraph S30) as the activity intake (Bq) of a radionuclide which would lead to an effective dose corresponding to the annual limit $E_{\mathrm{limit,w}}$, under the expectation that the worker is exposed to only this radionuclide. The ALI of radionuclide j is:

$$\mathrm{ALI_j} = \frac{E_{\mathrm{limit,w}}}{e(50)} \tag{B.5.7}$$

where $e(50)$ is the corresponding reference committed effective dose coefficient in (Sv $\mathrm{Bq^{-1}}$). The Commission recommended in *Publication 60* that the ALI should be based on the dose limit of 0.020 Sv in a year, with no time averaging.

(B 214) The DAC is the activity concentration in air in Bq $\mathrm{m^{-3}}$ of the radionuclide considered, which would lead to an intake of an ALI (Bq) assuming a gender-averaged breathing rate of 1.1 $\mathrm{m^3\,h^{-1}}$ and an annual working time of 2000 h (an annual air intake of 2200 $\mathrm{m^3}$). Then the DAC of radionuclide j is given by:

$$\mathrm{DAC_j} = \frac{\mathrm{ALI_j}}{2200} \tag{B.5.8}$$

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(B 215) The Commission does not now give ALI values, because it considers that, for compliance with dose limits, it is the total dose from external radiation as well as from intakes of radionuclides that must be taken into account as indicated above. It is, however, noted that the ALI concept can be useful in various practical situations, e.g., in characterising the relative hazard of radiation sources to ensure that appropriate administrative controls are in place.

(B 216) The DAC for inert gases which are not incorporated is limited by the effective dose arising from radiations incident on the body from the airborne activity. Thus the DAC is given by

$$\mathrm{DAC} = \frac{E_{\mathrm{limit,w}}}{2000\ \dot{e}_{\mathrm{sub}}} \tag{B.5.9}$$

where $\dot{e}_{\mathrm{sub}}$ is the effective dose rate coefficient [mSv m^3(Bq h)$^{-1}$] for submersion in an airborne cloud containing the noble gas radionuclide and 2000 h is the annual working time. For some radionuclides the DAC is limited by the dose to the skin.

B.5.6. Public exposure

(B 217) Public exposures can occur from natural radiation sources, which may be modified by human activities, from technical installations, or from combinations of such sources. The annual effective dose to members of the public is the sum of the effective dose obtained within one year from external exposure and the committed effective dose from incorporated radionuclides within this year. The dose is usually not obtained by individual monitoring as for occupational exposure but is mainly determined by environmental measurements, habit data, and modelling. It can be estimated from:

- Simulation and prediction of radionuclide levels in effluents from the technical installation or source during the design period;
- Effluent and stray radiation monitoring during the operational period; and
- Radioecological modelling (pathway analysis of environmental transport, e.g., from the release of radionuclides and transport through soil to plants to animals to humans).

(B 218) External exposures of individuals may occur from radionuclides released from installations and which are present in the air, soil, or water. Doses can be calculated from activity concentrations in the environment by modelling and computation.

(B 219) Internal exposures can occur by inhalation of airborne radionuclides from a cloud, inhalation of resuspended radionuclides, and by ingestion of contaminated food or water.

B.5.7. Medical exposures of patients

(B 220) The use of effective dose for assessing the exposure of patients has severe limitations that must be taken into account by medical professionals. Effective dose

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can be of value for comparing doses from different diagnostic procedures – and in a few special cases from therapeutic procedures – and for comparing the use of similar technologies and procedures in different hospitals and countries as well as using different technologies for the same medical examination. Such data have been reviewed by UNSCEAR (1988, 2000). For planning the exposure of patients and risk-benefit assessments, however, the equivalent dose or preferably the absorbed dose to irradiated tissues is the more relevant quantity. This is especially the case when risk estimates are intended.

(B 221) Medical exposures of patients to external radiation are commonly concerned with only limited parts of the body and it is important that medical professionals are fully aware of the doses to normal tissue in the irradiated fields. With low tissue weighting factors for skin and relatively low values for a number of other body tissues partial body exposure can result in appreciable equivalent doses to local tissues even though the corresponding effective dose may be small. Similar considerations apply to doses from intakes of radionuclides.

B.5.8. Application of effective dose

(B 222) The main and primary use of effective dose is to provide a means of demonstrating compliance with dose limits. In this sense effective dose is used for regulatory purposes worldwide.

(B 223) Effective dose is used to limit the occurrence of stochastic effects (cancer and heritable effects) and is not applicable to the assessment of the possibility of tissue reactions. In the dose range below the annual effective dose limit tissue reactions should not occur. Only in a few cases (e.g., an acute localised exposure of a single organ with a low tissue weighting factor such as the skin) could the use of the annual limit on effective dose be insufficient to avoid tissue reactions. In such cases local tissue doses will also need to be assessed.

(B 224) The calculation of reference dose coefficients for intakes of radionuclides and dose conversion factors for external exposures is based on reference anatomical data for the organs and tissues of the human body together with defined biokinetic and dosimetric models. The general approach is to monitor individuals or the environment and from these measurement data to assess the external exposure or radionuclide intake. The dose coefficients and dose conversion factors published by the Commission are then used to assess the effective dose from the exposure or the intake. The weighting factors used in the calculation of reference dose coefficients and conversion factors apply to a population of both sexes and all ages. Thus dose coefficients, and the reference models and weighting factors used in their calculation, are not individual specific but apply to a Reference Person for the purposes of regulatory control. Conversion coefficients or dose coefficients are calculated for a reference adult worker or a reference member of the public of a defined age group.

(B 225) The effective dose of a worker assessed by the sum of the measured personal dose equivalent, $H_P(10)$, and the committed effective dose estimated from results of individual monitoring of the worker, and ICRP reference biokinetic and dosimetric computational models, is called *dose of record*. Dose of record is assigned

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to the worker for purposes of recording, reporting, and retrospective demonstration of compliance with regulatory dose limits.

(B 226) Particularly in retrospective dose assessments for occupational exposures, information may be available that differs from the reference parameter values used in the calculation of dose conversion factors and dose coefficients. In such situations it may be appropriate, depending on the level of exposure, to use specific data in the assessment of exposure or the intake and calculation of doses. It is, therefore, important to distinguish between those parameter values that might be altered in the calculation of effective dose under the particular circumstances of an exposure and those values that cannot be changed under the definition of effective dose.

(B 227) In the assessment of effective dose in occupational situations of exposure to radionuclides, changes may reasonably be made to the physical and chemical characteristics of inhaled or ingested radionuclides to better assess intakes and exposures. These changes need to be notified. Examples of the use of material-specific data in the calculation of doses from inhaled radionuclides have been given in *Supporting Guidance 3* (ICRP, 2002).

(B 228) For retrospective assessments of occupational doses to specific individuals in situations where the radiation dose could exceed a limit or constraint, it may be considered appropriate to make specific individual estimates of dose and risk. Consideration might then be given to changes in dosimetric assumptions used to calculate absorbed doses, and organ-specific risk estimates relating to the age and sex of the individual and the radiation exposure. Such changes from reference parameter values are not consistent with the definition or intended use of effective dose. They should only be performed by radiation protection specialists, with the level of effort determined by the level of exposure. In such situations the changes of parameter values must be described.

(B 229) In cases of incidents and accidents that could give rise to tissue reactions (deterministic effects), it is necessary to estimate absorbed dose and dose rates to organs and tissues and to take into account dose–response relationships to assess the potential for radiation effects that are likely to occur above dose thresholds (NCRP, 1990; ICRP, 1989b). It should also be noted that, in cases of accidents involving high-LET radiations (neutrons and alpha particles), radiation weighting factors (w_R) applicable to stochastic effects do not apply to tissue reactions; values of relative biological effectiveness (RBE) relevant to tissue reactions should be used.

(B 230) Effective dose is a risk-related quantity based upon the consequences of whole body exposure. The w_T values are selected values that are chosen to take account of the contribution of individual organs and tissues to total radiation detriment from stochastic effects, in terms of cancer and heritable effects, on the basis of current epidemiological (or, for heritable effects, experimental) evidence. Furthermore, w_T values are averages applying to both sexes and all ages. While effective dose is sometimes used for pilot studies aimed at generation of hypotheses of effects of radiation on human health, it is not an appropriate quantity for use in epidemiological studies of radiation risks. Epidemiological analyses instead require estimates of absorbed doses to tissues and organs, taking full account, to the extent possible, of the circumstances of exposure and the characteristics of the exposed individuals in

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the study population. Similarly, absorbed doses, not effective doses, are required for calculations of probability of causation of cancer in exposed individuals.

(B 231) In summary, effective dose should be used for assessing exposure and controlling stochastic effects for regulatory purposes. It can be used to demonstrate compliance with dose limits and for dose records. Effective dose provides a convenient quantity for the assessment of overall radiation exposure, taking account of all exposure pathways, internal and external, for dose record keeping and regulatory purposes. Used in this way effective dose is a valuable quantity for practical radiological protection purposes although it is not individual-specific but applies to a Reference Person. In retrospective situations the assessment of effective dose gives an insight into the quality of radiological protection and gives information on whether the dose limits could have been exceeded.

(B 232) However, there are situations in which the use of effective dose is not appropriate, and individual organ and tissue absorbed doses should be used instead. These include epidemiological studies, assessment of the probability of causation of cancer, assessments of the possibility of tissue reactions, or assessments of doses when treatment or medical surveillance are needed.

B.5.9. Collective dose

(B 233) The dosimetric quantities for radiological protection discussed above refer to a Reference Person. The task of radiological protection includes optimisation and the reduction of radiation exposure of groups of occupationally exposed persons or of the public. For this purpose ICRP has introduced the collective dose quantities (ICRP, 1977, 1991b) which should be used and understood as instruments for optimisation. These quantities take account of the group of persons exposed to radiation from a source and of a specified time period of exposure. The quantities have been defined as the collective equivalent dose, S_T, which relates to a tissue or an organ T, and the collective effective dose, S (ICRP, 1991b). The special name of the unit of these collective dose quantities is the man sievert (man Sv).

(B 234) Collective effective dose is defined in *Publication 60* (ICRP, 1991b) as the integral over effective doses received by the population (paragraph A34). The Commission introduced both the collective equivalent dose and the collective effective dose. Since the intent of the collective quantities is to serve as an instrument in optimisation of radiological protection especially for occupational exposures, and the collective equivalent dose is used only in special circumstances, only the collective effective dose is discussed in the present Recommendations.

(B 235) In occupational exposure, the quantity collective effective dose is used for optimisation of planned exposure situations of a group of workers. The collective effective dose, and the distribution of individual doses, is assessed prospectively for different operational scenarios before starting the planned work. Collective effective dose is then used as a relevant parameter in the decision process for the choice of the operational scenario. Comparison of the prospectively assessed collective effective dose, and the sum of all individual effective doses obtained from monitoring data

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after the completion of the work, can provide relevant information for future optimisation procedures and radiation protection measures. Collective effective dose can also be used as an instrument for comparing radiological technologies in medical practices and comparing the same radiological technologies at different locations (e.g., different hospitals, different countries).

(B 236) The definition of collective quantities, as described above, has led people in some cases to use collective effective dose incorrectly for summing up radiation exposures over a wide range of doses, over very long time periods and over large geographical regions, and to calculate on this basis radiation-related detriments. However, such a use of collective effective dose would only be meaningful if there were sufficient knowledge of the risk coefficients for the detrimental radiation effects in all dose ranges which contribute to the collective dose (Kaul et al., 1987). Owing to the large uncertainties, such a knowledge of risk coefficients is not available in the very low dose range.

(B 237) In this context it has to be realised that the risk factors, e.g., for carcinogenesis at low doses, are obtained from the extrapolation of epidemiological data observed in dose ranges of medium and high radiation doses. As described in Section B.2, the extrapolation is based on the assumption of a linear dose effect relationship without a threshold (LNT model). The Commission considers that, in the low dose range, the risk factors have a high degree of uncertainty. This is particularly the case for very low individual doses which are only small fractions of the radiation dose received from natural sources. The use of collective effective dose under such conditions for detailed risk estimates is not a valid procedure.

(B 238) To avoid aggregation of low individual doses over extended time periods and wide geographical regions the range in effective dose and the time period should be limited and specified. The collective effective dose due to individual effective dose values between E_1andE_2 for the time period ΔT is defined as:

$$S(E_1, E_2, \Delta T) = \int_{E_1}^{E_2} E \left[\frac{\mathrm{d}N}{\mathrm{d}E}\right]_{\Delta T} \mathrm{d}E \tag{B.5.10}$$

The number of individuals experiencing an effective dose in the range E_1 to E_2, $N(E_1, E_2, \Delta T)$ is:

$$N(E_1, E_2, \Delta T) = \int_{E_1}^{E_2} \left[\frac{\mathrm{d}N}{\mathrm{d}E}\right]_{\Delta T} \mathrm{d}E \tag{B.5.11}$$

and the average value of effective dose $\bar{E}(E_1, E_2, \Delta T)$ in the interval of individual doses between E_1 and E_2 for the time period ΔT is:

$$\bar{E}(E_1, E_2, \Delta T) = \frac{1}{N(E_1, E_2, \Delta T)} \int_{E_1}^{E_2} E \left[\frac{\mathrm{d}N}{\mathrm{d}E}\right]_{\Delta T} \mathrm{d}E \tag{B.5.12}$$

(B 239) For a group of individuals, the collective effective dose S could also be calculated by:

$$S = \sum_{\mathrm{i}} E_{\mathrm{i}} N_{\mathrm{i}} \tag{B.5.13}$$

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where E_i is the average effective dose in the subgroup i, and N_i is the number of individuals in this subgroup (ICRP, 1991b).

(B 240) In the calculation and interpretation of collective effective dose, the following aspects should be considered and critically reviewed in order to avoid a misuse of collective effective dose:

- Number of exposed individuals;
- Age and sex of exposed persons;
- Range of individual doses;
- Dose distribution in time; and
- Geographical distribution of exposed individuals.

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B.6. Uncertainties and judgements in radiological protection

(B 241) In *Publication 60* (ICRP, 1991b) the Commission stressed, as has been done in this document, that the assessment of radiation dose is fundamental to radiological protection, although neither the equivalent dose in an organ or tissue nor the effective dose can be measured directly. In the evaluation of these doses, models are necessary to simulate the geometry of the external exposure, the biokinetics of the intake and retention of radionuclides in the human body, and the human anatomy. Dosimetric considerations with respect to methodology and practical use are also of great importance.

(B 242) These models and their parameter values have been developed in many cases from experimental investigations and human studies in order to derive 'best estimates' of model parameter values. It is recognised that there may be large uncertainties in the values of some of the parameters and in the formulation or structures of the models themselves. Some of these uncertainties have been addressed in various publications (Leggett et al., 1998, ICRP, 2002, Harrison et al. 2001, Likhtarev et al., 2003) and estimates of the illustrated variability of parameter values, e.g., for physiological and anatomical characteristics have been demonstrated (ICRP, 2002). Such variations of parameter values are of particular significance with respect to the models necessary for dose assessments from internal exposure. From situations with a broad range of values the necessary parameters are selected by judgements in order to evaluate weighting factors and other parameters for the dose assessment.

(B 243) It is important to distinguish between uncertainty and variability. Uncertainty refers to the level of confidence that can be placed in a given parameter value or prediction of a model or estimate of the central value of dose for a population. Uncertainties of the measurements in the low ranges of the determined parameters are included. It is an important factor in all extrapolation procedures and particularly in assessing radiation doses and their effects in the low dose range.

(B 244) Variability (strictly, biological variability) refers to quantitative differences between different members of the population in question, e.g., with respect to their physiological and metabolic parameters. For example, two healthy persons of the same age and sex and having identical diets may exhibit substantially different rates of transit of material through the colon. Similarly individual members of a population will show substantial variation in the uptake of radioiodine by the thyroid for the same initial intake. Variability will be an important source of uncertainty in the estimate of a central value when the estimate is based on a few, highly variable observations.

(B 245) Risk factors for stochastic effects, from which w_R and w_T values are derived, have been obtained from epidemiological and experimental radiobiological data in the medium and higher dose ranges. The risk factors for the lower dose ranges that are important for radiological protection as well as the concept of effective dose, are based on extrapolation from the measured data in the higher dose ranges using the linear-non-threshold model (LNT model).

(B 246) This model is an assumption which has not been scientifically validated. It is considered to be the most appropriate interpretation of current experimental and

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epidemiological data and is consistent with current understanding of stochastic radiation effects. However, its use also introduces a high degree of uncertainty, especially in relation to exposures at low doses and low dose rates (UNSCEAR, 2000). The assumed linearity of dose–response, and the additivity of doses are necessary conditions for the concepts used in radiological protection in the low dose ranges, especially for the use of effective dose, as described in previous sections.

(B 247) The uncertainties which are associated with the assessment of radiation doses and health detriments have been discussed in various sections of this document. Some of the more important factors considered are:

- The heterogeneity of energy deposition within tissues has been described in the low dose ranges of external as well as of internal exposures (Section B.3.2).
- The heterogeneous distribution of radionuclides has been described in the body and in tissues which is especially significant when considering ionising particles with short ranges such as alpha particles (Sections B.3.2, B.3.3).
- For dose assessments from internal exposures, the biokinetic models and their parameter values are variable and dependent on the specific conditions of exposure. Frequently, animal data have to be used and to be extrapolated to humans.
- Human populations vary worldwide on ethnic grounds with respect to physiological and other parameters (ICRP, 2002). Variability can become large when radioecological models are used to assess concentrations of radionuclides in food, and hence intakes from habit data as the parameters are frequently very uncertain, biological variability is large, and measured activity values are frequently low.
- The RBE values which are important for the choice of w_R values vary with the end point considered and the experimental design. Frequently the values rely on animal and in-vitro data (Section B.3.5, paragraphs B 73 – B 131).
- The target cells for the induction of cancer and their location in tissues are unclear. The dose response in the low dose range for stochastic effects, the mode of extrapolation and the LNT model are uncertain (Annex A).
- For the estimation of parameters connected to the assessment of health detriments, sex averaging is performed which causes uncertainty (Section B.3.4).

(B 248) The degree of uncertainty varies for the various parameters and different circumstances in defined exposure situations. Therefore, it is not possible to give general values of uncertainties, but considerations of this kind should be and have been made for special cases and should be included in comprehensive evaluations (e.g., CERRIE, 2004, ICRP, 2006c). In general it can be said that uncertainties in the assessment of radiation doses from internal exposures including the biokinetics of radionuclides are larger than those from external exposures. The degree of uncertainty differs between various radionuclides.

(B 249) The Commission is aware of these uncertainties, and efforts are being undertaken to critically evaluate and to reduce them wherever possible. However, for prospective dose assessments in regulatory processes the Commission takes the position that the dosimetric models, as well as the parameter values that it recommends for determining doses from quantitative information about radiation fields at working places and in the environment or from intakes of radionuclides, should

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be taken as reference models. These values have been fixed by convention and are not subject to uncertainty.

(B 250) Equally the Commission considers that the dosimetric models and parameter values which are needed for the purpose of recommending dose limits or constraints are defined as reference data and, therefore, are not uncertain. Nevertheless, these models and values are re-evaluated periodically and may be updated by ICRP on the basis of such evaluations when new scientific data and information become available.

(B 251) It should be noted that the dosimetric models, conversion coefficients, and other parameters recommended by the Commission have been developed principally and primarily for planning and assessing normal occupational exposures, for planning for discharges into the environment and for generic assessments of doses. They are needed to demonstrate compliance with dose limits. These are circumstances in which doses are low (Section B.5.5). At higher doses, for example following accidental exposures, or for epidemiological studies, more specific information on the individual and the exposure conditions are needed. In such situations all sources of uncertainty should be taken into consideration including the variability of individual anatomical and physiological data, specific information on radionuclide source-term, biokinetics, and the direction of radiation incidence in cases of external exposure.

(B 252) In conclusion, the reference models and their parameter values have been developed for use in prospective radiological protection. These models and parameter values are also used for demonstrating compliance with dose limits when exposures are low but in general should not be used for individual risk estimates or for epidemiological studies. In cases where this is done the uncertainty must be critically reviewed. If such individual data are not available the reference parameters may be used but this must be clearly documented. This limitation of usage applies particularly to effective dose. For the assessment and judgement of individual cases absorbed doses to organs or tissues should be used together with the most appropriate biokinetic parameters, data on biological effectiveness of the ionising radiation and risk coefficients. In these cases uncertainties should be taken into consideration.

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A woman dances with her son

because of brain surgery that
reduced her epileptic seizures

performed by a neurosurgeon who was
able to pinpoint the foci of the seizure

due to breakthroughs in the
mapping of the human brain

advanced by physicians, mathematicians
and computer engineers around the world

inspired by new discoveries
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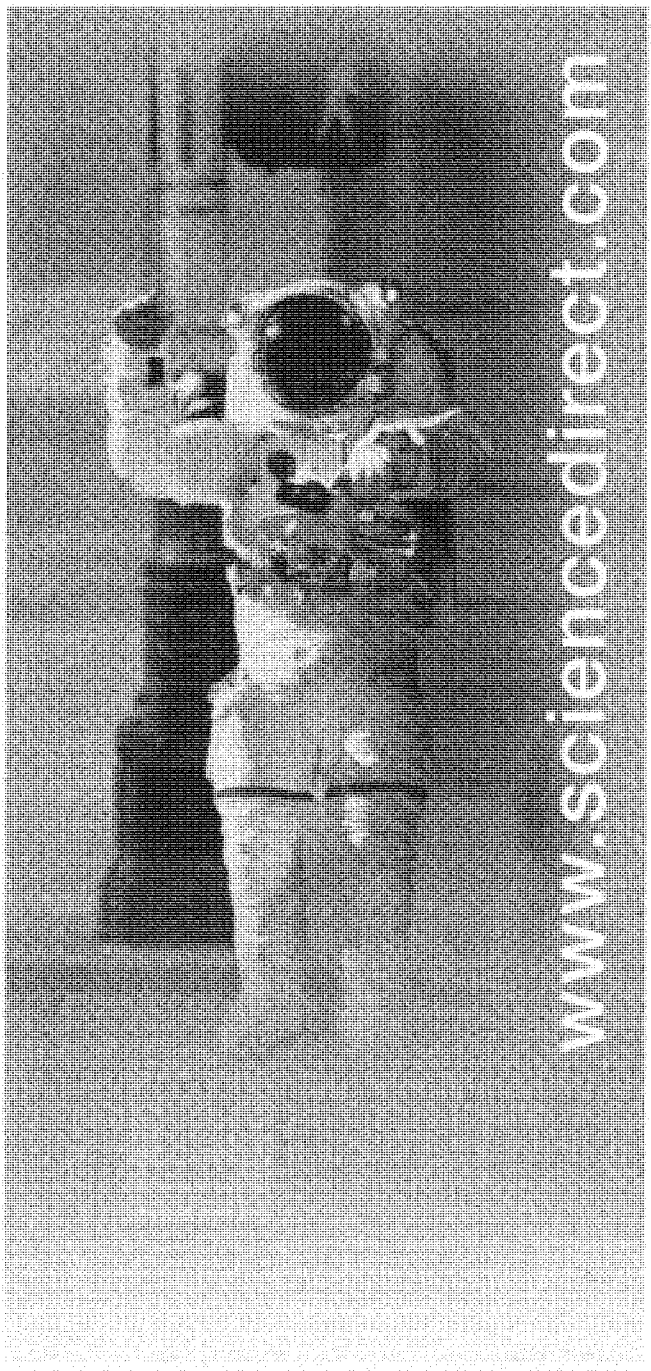

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IN THE UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

REQUEST FOR APPROVAL OF ADDITIONAL USES OF PHOSPHOGYPSUM PURSUANT TO 40 C.F.R. § 61.206

Submitted by: **The Fertilizer Institute on Behalf of Its Members**

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I. INTRODUCTION

The Fertilizer Institute[1] (TFI) submits this petition in support of a request for approval of the use of phosphogypsum material (PG) in road construction pursuant to the United States Environmental Protection Agency's (EPA) rule governing the distribution and use of phosphogypsum for other purposes. See 40 CFR §61.206.[2] TFI will supplement this submission to include a report interpreting the recent measurements of the radioactivity level of PG in U.S. stacks, an economic report on regulatory cost savings, and, if necessary, other information. Consistent with past approvals, EPA will make the "EPA Approval" publicly available, along with the Petition and any information EPA relied upon for making its determination. EPA may decide to respond to relevant stakeholder comments in connection with the Petition. TFI will provide additional information, where requested or deemed appropriate.

TFI's application includes the Petition, Appendix 1 (summary of the Risk Analysis), Appendix 2 (radionuclide exposure and risk calculation), Appendix 3 (metals screening report), and Appendix 4 (other documents being submitted for the administrative record).

PG is a byproduct of the phosphate fertilizer production process. At a typical U.S. facility, approximately five tons of PG are generated per ton of fertilizer produced. Prior to 1989, PG was reused in various applications (including, among other uses, in the construction of roads and in agriculture). In 1989, EPA restricted the use of PG based on concern with naturally occurring radioactive material (NORM) in PG. Specifically, EPA's National Emission Standards for Hazardous Air Pollutants (NESHAP) Subpart R requires that, with very limited exceptions, PG must be placed in engineered above ground impoundments (commonly referred to as "gypstacks").[3] The existing approved alternative uses include use of no more than 7,000 pounds of PG for indoor research, use of PG with an average radium-226 concentration not exceeding 10 picocuries per gram (pCi/g) for agricultural application as a soil amendment, and use of PG as landfill cover in a test cell to determine if it can be utilized more broadly as a landfill cover.[4]

Since 1989, scientific studies have been completed in the U.S. and internationally supporting expanded beneficial reuse; these studies demonstrate protectiveness of human health and the environment. PG is reused in many countries outside the U.S. in agriculture, mine restoration, building materials, marine applications, daily landfill cover, and for road construction as

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[1] TFI is the leading voice of the fertilizer industry, acting as an advocate for fair regulation and legislation, a consistent source for trusted information and data, a networking agent, and an outlet to publicize industry initiatives in safety and environmental stewardship. The fertilizer industry contributes $155 billion to the nation's economy. TFI, available at https://www.tfi.org/policy-center/economic-impact. The fertilizer producers, wholesalers and retailers, along with the businesses that serve them, support nearly half a million U.S. jobs with total annual compensation of $36 billion. *Id.*

[2] EPA, National Emission Standards for Hazardous Air Pollutants; Radionuclides, 54 Fed. Reg. 51,654 (December 15, 1989) (1989 Rule).

[3] 40 CFR §§ 61.200 - 201.

[4] 40 CFR §§ 61.204 - 61.205.

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requested herein. Also over the years, EPA has also developed more specific and scientifically supportable guidance governing risk assessments.

This Petition seeks approval of the use of PG in road construction in light of the new scientific and factual information. The Petition includes an Executive Summary (Section II), explanation of the Relief Requested and the Petition Process (Section III), regulatory history and changing conditions (Section IV), summary of the evaluations performed (Section V), and an application of the risk management factors to the use of PG in road construction (Section VI).

II. EXECUTIVE SUMMARY

Requested Relief

Section III of the Petition requests a waiver of the requirement that PG be placed in stacks and approval of the beneficial use of PG in road construction pursuant to EPA's rule governing the distribution and use of phosphogypsum for other purposes. In 1989, EPA restricted the use of PG, requiring it to be stacked due to concern with naturally occurring radioactive material (NORM) in PG. Since the 1989 restriction, scientific studies have been completed in the U.S. and internationally supporting expanded beneficial use and demonstrating protectiveness of human health and the environment. PG is reused in many countries outside the U.S. in agriculture, mine restoration, building materials, marine applications, daily landfill cover, and for road construction as requested herein. EPA has in the same timeframe developed more specific and scientifically supportable guidance governing risk assessments. This petition provides the necessary information regarding safe use of PG for road construction along with economic and other benefits.

Specifically, TFI requests that the EPA Assistant Administrator of the Office of Air and Radiation (OAR) approve a waiver of the requirement that PG must be placed in stacks to allow the use of PG in road construction as road base, paving and various combinations of road base and paving of roadways. Key considerations underpinning this petition include:

1. All reasonable maximum exposures (RMEs) resulting from use of PG are less than the 3 in 10,000 lifetime cancer risk EPA has determined safe for alternative PG uses and well below natural background exposure. Thus, as stated in EPA's alternative PG use guidance (entitled *Applying to EPA for Approval of Other Uses of Phosphogypsum: Preparing and Submitting a Complete Petition under 40 CFR 61.206*),[5] the use of PG in road construction is at least as protective as placement of phosphogypsum in a stack, consistent with the regulations.

2. This Petition for PG reuse in road construction and the requested EPA approval covers any paved road, i.e., unpaved roads have not been included in the analysis. The risk

[5] EPA Guidance: *Applying to EPA for Approval of Other Uses of Phosphogypsum: Preparing and Submitting a Complete Petition under 40 CFR 61.206: A Workbook*, at 13 (2005) (EPA PG Workbook), *available at* https://www.epa.gov/sites/production/files/2015-05/documents/wrkbk_sub-r_appl_1105.pdf. The Office of Radiation and Indoor Air Workbook's purpose is "to provide information on how to prepare a complete petition to the U.S. EPA for the distribution and use of phosphogypsum for 'other purposes' that is consistent with the requirements of our regulations for radon emissions from phosphogypsum stacks." *Id.* at 1.

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analysis conducted to support this Petition uses an average radioactivity level (radium-226) of 27 pCi/g that is similar to levels EPA has previously used. To account for some potential variability (~30 percent) that has been observed in past testing, the relief sought in this petition seeks approval to use PG containing radioactivity levels of up to an average of 35 pCi/g in road construction materials.[6] EPA's past PG testing indicates that the average per stack is bound by this value. As a point of illustration, the radioactivity level would have to be 148 pCi/g to be equivalent to EPA's "safe" risk level of 3 in 10,000 (see Appendix 2). The average level of 35 pCi/g sought in this petition is over 4 times less than this equivalent safe level.

3. This Petition proposes self-implementation by the owner or operator with notice to EPA. Specifically, this means that the owner or operator of the PG stack from which PG is removed for road construction will submit a certification to EPA on a project by project basis. This requires the owner/operator to notify EPA that a local, state or federal transportation agency or company has requested to use PG in its road construction project. The notice will include: certification that the PG removed from the stack is consistent with EPA's approved limit under this Petition, and the location where the PG will be used in road construction (i.e., GIS coordinates of the road location). No sampling is required since the existing data demonstrates that the average radioactivity level does not exceed 35 pCi/g, and that this level is far below a safe level of 148 pCi/g.

The petition is supported by a Risk Analysis that examines radiological risks of the proposed use of PG in road construction and ultimate disposition of PG in newly constructed roads, along with a screening evaluation that concludes a numerical risk assessment of metals within the PG is not necessary.

The Risk Management Decision

Section IV provides TFI's justification for approval of this Petition. The decision to approve a new use for PG must be made by the Assistant Administrator for Air and Radiation. As a matter of policy, the decision involves weighing results of a risk assessment, technical analyses, and other factors. This Section summarizes these factors as TFI submits they should apply to EPA's risk management decision.

The justifications detailed within the petition include:

1. The Risk Management limit of 3 in 10,000 is consistent with other NESHAP risk limits.

2. The highest Reasonably Maximum Exposure (RME) for the use of PG in road construction, 0.5 in 10,000 (0.5 in 10,000 is 5 in 100,000), is well below the NESHAP radionuclide risk management limit of 3 in 10,000.

3. For ease of calculation, this Risk Assessment used a nominal average radioactivity level in PG of 27 pCi/g. By "nominal average" we mean this is the

[6] The Petition seeks approval of up to an average of 35 pCi/g because this average level represents the highest average level identified in prior testing by EPA.

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average radioactivity level we used in our initial calculation. This number is reasonable and is similar to numbers EPA previously used. Once the risk from the initial calculation is determined, EPA can then estimate the risk from higher and lower radioactivity levels. For example, if the average radioactivity level for a stack is 13.5 pCi/g, then the risk is one half of that calculated for 27 pCi/g.

4. At EPA's request, TFI members recently sampled PG from multiple gypstacks (up to approximately 10 composite samples per stack). A summary report (including any other appropriate data and evaluations) will be submitted. We expect this report will confirm that the existing data supports the use of the PG stacks in the U.S for use in road construction. In summary, the average radioactivity level for each stack tested to-date was significantly lower than 27 pCi/g. Furthermore, the risk assessment performed for this Petition demonstrates that 27 pCi/g corresponds to a cancer risk of 0.5 in 10,000 for the highest RME use of PG in road construction (i.e., the road construction worker), therefore the risk from these stacks is less than 0.5 in 10,000.

5. Based on the risk assessment performed for this Petition, EPA's PG risk management safe risk level of 3 in 10,000 corresponds to a radioactivity level in the PG of 148 pCi/g (see Appendix 2). Thus, PG materials in TFI's member's stacks may be safely used as road construction material. It is extremely unlikely if not impossible for random variation in the PG radioactivity levels to exceed an average 148 pCi/g, the radioactivity level that corresponds to a 3 in 10,000 risk management level.

6. EPA performed extensive modeling of the likely migration of radionuclides from PG used in road construction in a 1992 assessment discussed below. The EPA concluded that the radionuclide "doses from the groundwater pathways are all zero." EPA's assessment demonstrates that the radionuclide risks were found to be zero.

7. Screening evaluation of the potential impact of metals in PG shows that PG can be used safely by workers in road construction. Paving limits direct contact by the community and also limits water contact with PG isolated in the base layer.

8. Care has been taken in the assessment process to manage scientific uncertainties by choosing values and approaches that are likely to overestimate rather than underestimate risks. These result in an RME value, which serves as a reasonable upper bound on the risk distribution and is a readily accepted approach for representing maximum exposures (see Appendix 2). It also provides insight into risks to the population. RMEs overestimate risks for highest exposure situations such that actual risks would be lower.

9. For perspective on exposure magnitudes, radiation levels from use of PG are compared to naturally occurring background. Each exposure scenario has incremental radiological doses that are well below naturally occurring background levels. Exposures to the public using the road or living immediately adjacent to the road are likely to be indistinguishable from the natural variability in background.

10. There are naturally occurring background radiation and metals in other non-PG construction material including coal ash, fly ash, bottom ash, and other common construction materials. These materials have been deemed safe to use in road construction and other applications. Similarly, this Petition demonstrates the same is true for PG.

11. The reuse of PG for road construction is consistent with EPA policy on recycling of wastes and waste residuals.

12. The use of PG for roadway construction provides a net economic benefit.

13. Approval of the use of PG for road construction is consistent with the Administration's Regulatory Reform Policies.

Risk management factors favor approving the use of PG for road construction. The petition and supporting risk analysis demonstrates that this use can be advanced safely.

Factors Influencing Future Uses of PG

A number of factors influence the future uses of PG and are the impetus for this petition:

1. The current requirement to obtain regulatory approval for each and every application of a new use is unwieldy and unnecessarily slows the process of implementing new uses; as a result, it impedes innovation and economic efficiencies.

2. The economics of gypstacks have changed. The cost to stack and manage gypstacks has increased beyond original expectations.

3. New data are available on the average level of radioactivity in the PG.

4. There is a better understanding in the scientific community concerning radiation protection and management related to PG reuse. More than a dozen beneficial uses have been analyzed worldwide, resulting in significant, successful PG reuse applications in at least 21 countries.

5. U.S. risk assessment approaches have progressed based on experience, analytical advances, and evolving environmental management policies since the 1980s, along with increased awareness of product lifecycles and sustainability.

6. EPA policies encourage reuse and recovery of high-volume, low-risk waste. This includes increased emphasis on understanding product lifecycles and adopting sustainability policies.

7. Perceptions of gypstacks have changed. EPA's 1989 final rule did not anticipate the range of public sentiment regarding the long term presence of gypstacks, public pressure to cease this practice is growing.

Beneficial Use of PG in Road Construction

PG may be used as road base when mixed (e.g., at or less than 50%) with other materials such as soil, sand or aggregate or in the surface pavement (e.g. at approximately 2.5%). The calculation is based on equal amounts of PG and soil in roadbed. This is an upper bound because industry practice recommends similar ratios or less and EPA's 1992 risk assessment used 33.3 percent PG to 66.6 percent soil (see Appendix 2). As shown in Figure 1, road base is a supporting layer of material approximately 0.25 m thick beneath the pavement and above underlying sub-grade. The design of new roads is as depicted in Figure 1. The potential for direct exposure is limited by placing the PG road base under the surface pavement, which isolates it from groundwater and surface water, i.e., it prevents the PG from directly contacting people or water (groundwater or surface water). The constructed road also affords a degree of radiation shielding for people driving on the road or for residents living nearby. Section IV describes the use of PG in road construction in detail.

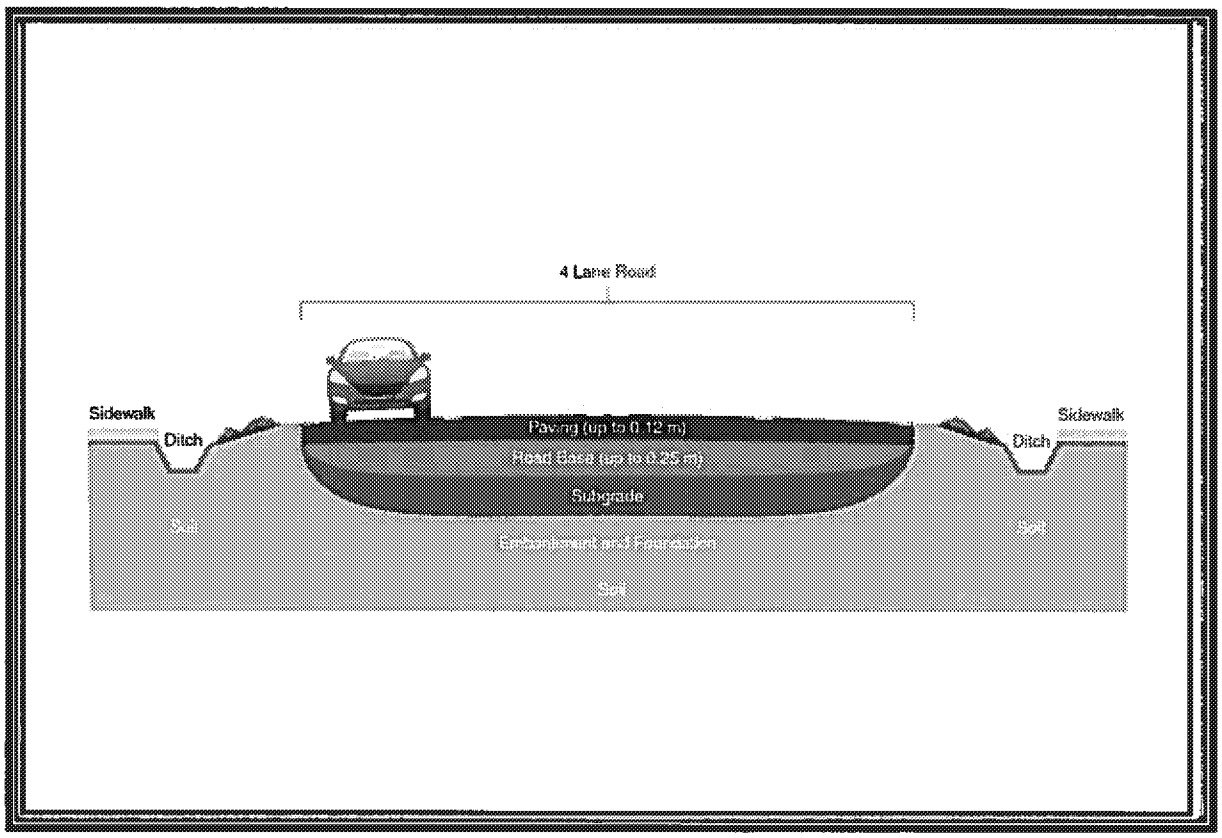

Figure 1 provides a conceptual view; municipal roads can vary in width and structure.

The risk analysis shows that PG can be used safely for road construction. Opening this possibility for PG use brings a number of benefits consistent with now accepted environmental philosophies of emphasizing reuse and sustainable infrastructure. The petition details the factors for EPA to consider as it evaluates this petition.

TFI's Petition and supporting risk analysis were developed consistent with the EPA PG Workbook, prior Petitions, and a series of working meetings with EPA staff, with EPA input and

direction on key elements of the analysis. The complete analysis for PG reuse in road construction, including methodologies and other aspects, is provided in this Petition and attached appendices.

Consideration of Risks

This text box provides some basic concepts and definitions to aid the reader's understanding of the Petition.

Many substances (often naturally occurring substances) are radioactive. The basic concepts relevant to this Petition are:

- **Radioactivity** is a measure of the amount of gamma rays, alpha or beta particles, x-rays, or neutrons that disintegrate from a gram of the substance being measured (in our situation, in each gram of PG). The amount of radioactivity in a gram of a substance is measured in curies (Ci) or becquerels (Bq). One curie is 3.7×10^{10} radioactive decays per second, roughly the amount of decays that occur in 1 gram of radium per second. A Becquerel is one disintegration per second. Historically, scientists originally used units of Ci. The International System of Units (ISU) now uses Bq.

  A picocurie (pCi) is one-trillionth of a curie.
  1 Bq = 2.70×10^{-11} curies = 0.027 pCi

- **Dose**: Dose measures the amount of radiation absorbed by a person. The terms radiation absorbed dose (rad) and gray (Gy) describe measurements of the absorbed dose.

  1 gray (Gy) is equivalent to 100 rad; 1 rad = 0.01 Gy

  Dose equivalent (or effective dose) adjusts the absorbed dose to include the relative medical effects of gamma rays, alpha or beta particles, x-rays, or neutrons, e.g., the effects of alpha and neutron radiation are more damaging to the human body than gamma radiation.

  The dose equivalent is measured in rems (roentgen equivalent man) or 1/1000th of a rem (millirem or mrem). A rem for each type of radiation is equal to the absorbed dose (in rads) times a quality factor that reflects the fact that some types of radiation cause more damage than others [see "Units of Radiation Dose," 10 CFR § 20.1004]. The scientific community is shifting to use the nomenclature developed for the international system unit, so the term sievert (Sv) is often used.

  1 rem = 0.01 sievert (Sv); 1 sievert (Sv) = 100 rem; 1 millisievert (mSv) = 0.1 rem or 100 mrem.
  100 rem is equivalent to 1 Sv or 0.1 rem (or 100 mrem) equals 1 mSv); and

- **Risk**: The regulatory risk assessment process converts a dose equivalent (in mrem) into an upper bound risk (or probability) of developing fatal cancers. It is based on a regulatory assumption that the dose equivalent may cause harmful effects and as the magnitude of this dose increases or decreases, the risk increases or decreases, respectively, linearly (e.g., if the dose is halved, the calculated risk is halved). The risk assessment performed for this Petition concludes that an effective dose of 600 millirem corresponds to a risk of 3 in 10,000 (i.e., if all of the protective assumptions are valid, 3 in 10,000 people may develop a fatal cancer). The actual risk is likely to be lower.

Generally, the sources for this explanation include EPA, *Radiation Terms and Units, available at* https://www.epa.gov/radiation/radiation-terms-and-units; NRC, available at https://www.nrc.gov; MIT News, *Explained: rad, rem, sieverts, becquerels A guide to terminology about radiation exposure, available at* http://news.mit.edu/2011/explained-radioactivity-0328; National Acronautics and Space Administration, *Radiation Math, available at* https://www.nasa.gov.

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Radiological Risks Associated with Using PG for Road Construction

Five relevant and appropriate exposure scenarios were defined based on discussions with EPA and knowledge of how exposures might occur to workers and the public from using PG in road construction: Truck Driver (transporting PG), Road Construction Worker, Utility Worker, Road User (auto, motorcyclist, or bicycle), and Nearby Resident. The risk assessors chose exposure values such that each exposure scenario represented an RME (exposures are expressed in terms of millirems (mrem)) (see Appendix 2 and text box above). Exposure estimates are developed for each scenario by considering the activities within each group, distance from the potential source, duration of exposure, and physical barriers that serve to shield or reduce exposure.

This information is used as input in one of two accepted radiological exposure models as appropriate to the scenario – MicroShield and RESRAD (as agreed to with EPA). Exposure estimates are converted to cancer risk by using an accepted dose-response relationship (i.e., a linear no-threshold (LNT) dose-response relationship established by the International Commission on Radiological Protection (ICRP)). This is used to evaluate potential health effects from low-level radiological exposure associated with using PG in road construction. The LNT model presumes a straight line slope relationship between exposure and risk with the straight line passing through 0 and as a result any exposure no matter how small, is assumed to have a corresponding risk estimate; this is why it is referred to as "no-threshold" (see Uncertainty Analysis in Section VI). Utilizing an exposure-risk relationship derived with the LNT model helps ensure that risk estimates are more likely to be overestimated than underestimated.

The exposures can also be compared to the level in mrem associated with the RME, which is a value of 600 mrem (dose equivalent to a risk of 3 x 10,000). The level of exposure serves to indicate whether a dose or risk estimate is above or below a risk management level. Exposures below the risk management level of 600 mrem are deemed safe by EPA. The PG reuse exposure scenarios examined for radiological risks were lower than the EPA risk management limit of 3 in 10,000 (Table ES-1).

Of the scenarios evaluated, the highest estimated dose and risk is for the road construction worker who lays down the road base containing PG. The RME for such individuals results in a dose of 22 mrem/year while engaged in road construction and 110 mrem for the total exposure period. This estimated annual exposure of 22 mrem is a fraction of naturally occurring background radiation (310 mrem/year national average with a range of 100 to 1,000) (see Appendix 2). The exposure dose is also over 5 times less than the risk management safe dose of 600 mrem and risk limit of 3 in 10,000.

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Table ES-1. Dose and Risk Summary for All Scenarios

Receptor	Site	Exposure Duration (years)	Exposure Dose (mrem)	Estimated Cancer Risk	Background Dose (from Exposure Duration) (mrem)	Exposure Dose Percentage of Background Dose (%)
Accessible Roadway Exposure Scenarios						
Road Construction Worker	PG in Road Base	5	110	0.5 in 10,000	1550	7%
Road User (Motorist/Bicyclist)	PG in Road Base & Surface	26	28	0.1 in 10,000	8060	0.3%
Truck Driver	PG-Containing Material for Road Base	5	93	0.5 in 10,000	1550	6%
Nearby Resident	PG in Road Base & Surface	25	16	0.08 in 10,000	8060	0.2%
Utility Worker	PG in Road Base	1	0.8	0.004 in 10,000	310	0.3%
	EPA Cancer Risk Management Goal		600	3 in 10,000	600	

Estimated cancer risk below this goal.

Risks to the public using the road or living immediately adjacent to the road were much lower than those for a road worker. These results indicate that PG can be used safely for road construction.

Naturally occurring background radiation varies geographically in a broad range of 100 to 1,000 mrem/year for the various states. The average background radiation (generally 310 mrem per year, although background varies locally) is also used to gauge exposures. For example, a 5-year exposure at average natural background corresponds to 1,550 mrem of cumulative background radiation exposure. Similarly, 26 years of exposure corresponds to a cumulative background radiation of 8,060 mrem. These naturally occurring average values are well above the exposure dose calculated in the Risk Assessment for use of PG in road construction.

Ultimate Disposition of Roads Containing PG

The Risk Analysis includes a calculation of exposure for a realistic ultimate disposition of a new road constructed with PG. New roads serve as an established part of municipal (county, state and/or federal) infrastructure and as such would require periodic repair and expansion as needed. These activities could include removing the surface and grinding and reusing or disposing of the materials consistent with federal and state and local regulations. Exposures and risks associated with maintenance of roads and reuse of construction materials are expected to be comparable to or less than those detailed in the risk assessment for road construction.

"Reclaimer Exposure Scenario"

EPA requested that the risk analysis report include a "Reclaimer Exposure Scenario" (i.e., the road is abandoned, the land cleared for construction, and a house constructed on land containing a mixture of PG, soil, and fill). The length of exposure is 26 years (i.e., 90% of the population lives in their house 26 years or less). This was the RME length of residency used for the residential exposure in EPA's 1992 Risk Assessment and in EPA guidance. The Risk Analysis concludes that the reclaimer scenario is not an appropriate RME exposure (it is not reasonably realistic in the real world). The in-place abandonment of municipal infrastructure and allowance for construction of residences on top of these abandoned roads runs counter to current road and homebuilding construction practices. Despite this, the Reclaimer Exposure Scenario was evaluated with improvements to the 1992 assumptions. First, a home would not be constructed on an abandoned road without first removing the surface layer and regrading, which would mix and dilute the PG. Second, the house would also not be built on the remixed PG without inclusion of a foundation and vapor layer. Thus, although the Reclaimer Exposure Scenario is

not expected to occur, the refined assumptions and calculations in the Risk Analysis represent an extreme upper bound, and not an RME, on future hypothetical exposure. The Reclaimer Exposure Scenario therefore should not be used for an EPA risk management decision concerning whether to approve the road construction use of PG. However, even this extreme bound on the hypothetical future exposure presents a risk below the EPA risk management safe level limit of 3 in 10,000.

From a screening-level perspective, although not a RME exposure, this extreme hypothetical scenario (undertaken at EPA's request) demonstrates that a numerical risk on the ultimate disposition scenarios need not be calculated.

The Screening Level Analysis of the Potential for Radionuclides in PG Impacting Groundwater

EPA performed extensive modeling of the likely migration of radionuclides from PG used in road construction in its 1992 Background Information Document (BID) assessment.[7] The BID concluded that the radionuclide "doses from the groundwater pathways are all zero."[8] The soil partition coefficient was arbitrarily decreased and still "no radionuclides are calculated to reach the onsite well via the groundwater pathway" nor are any "radionuclides calculated to reach the off-site river or well via groundwater."[9] This assessment demonstrates that the radionuclide risks were found to be zero.

Since this extensive modeling found no impact, no additional evaluation was deemed necessary in this Petition.

Screening Level Risk Analysis of Metals

The Risk Assessment's screening of metals considered two pathways: direct contact and potential for leaching. With regard to worker exposure during construction, a screening-level analysis was performed during which the concentrations of metals within PG were compared to EPA screening-level values. For the most part, all maximum metal concentrations in PG were less than EPA screening levels. The only two that initially exceeded their respective screening levels were lanthanum (La) and zirconium (Zr). The zirconium (Zr) level, however, is still within background levels. Upon mixing in either pavement or road base, the lanthanum (La) values are expected to fall below screening levels. Because the road materials are not accessible upon completion, there is no direct contact pathway from PG construction materials to residents or road users.

The second pathway considered was potential for leaching to or influence on surface water bodies and groundwater. Given that the road base is located above the water table and that the PG material is isolated and not directly exposed to surface runoff, the potential for contact of the road base with water is extremely limited. This minimizes the potential for leaching to

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[7] EPA, Potential Uses of Phosphogypsum and Associated Risks, Background Information Document, 402-R92-002, Table 2-5 (May 1992) (EPA 1992 BID).

[8] *Id.* at 4-17.

[9] *Id.* at 4-17, 4-31, 4-34, Scenarios 8, 11, Tables 4-5, 4-18, Footnote C, among other sources.

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groundwater. Nevertheless, the Risk Analysis considered the nature of roads and available information on leaching of metals from the PG.

For comparison, we looked at the metals content in PG, other road construction material (such as fly ash), and metals in biosolids continuously applied on agricultural fields (see Appendix 3). All road construction materials have some level of naturally occurring radioactive materials and metals/metalloids. The maximum concentrations reported in the literature for PG were compared with reported median concentrations in fly ash and Portland cement. Approximately half the median concentrations of metals in fly ash are higher than the maximum concentrations reported for PG. Aluminum and iron concentrations are approximately 16 times higher in fly ash than in PG. Boron, barium, beryllium, lead, and vanadium are between approximately 3 to 7 times higher in fly ash compared with PG and other constituents such as arsenic, chromium and manganese are slightly higher in fly ash.

Potential for leaching of metals and associated potential for groundwater impacts from agricultural lands receiving biosolids have already been addressed in other EPA assessments and found not to be a significant source of risk.

Moreover, the footprint of a road on the landscape is very small compared to agricultural lands upon which biosolids and amendments containing higher metals than those in PG are permitted for use. The smaller areal footprint and lower likelihood of leaching from a constructed road compared to an agricultural field indicates that the influence on groundwater from PG in the road is likely to be comparatively very small. PG in road base is expected to be negligible in comparison and thus can be used safely in road construction given the lower metals content in PG and the smaller spatial footprint and confinement of the base layer above the water table. In any case, environmental and highway construction practices already address these risks.

Conclusion of Risk Analysis

The road construction scenarios discussed herein were evaluated for numerous risks (e.g., a broad scope of RME radiological exposures and non-radiological constituents present in PG). The analyses clearly demonstrate that:

- Use of PG in road construction presents no greater risk than stacking of the material; and

- PG can be safely used in road construction. In scientific terms, the use presents a risk of $< 3 \times 10{,}000$, a level deemed by EPA to be safe (see discussion below).

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III. RELIEF SOUGHT AND THE PETITION PROCESS

A. Specific Relief Sought

This PG reuse Petition requests the following:

> U. S. Environmental Protection Agency (EPA) action, pursuant to 40 CFR § 61.206, on the Petition submitted by The Fertilizer Institute (TFI). The requested action includes granting a waiver of the requirement that phosphogypsum (PG) be placed in stacks and an approval to allow the use of PG containing up to an average of 35 pCi/g in road base, paving, and various combinations of road base and paving of roadways.

TFI's Petition demonstrates that with PG used as construction material, the highest RME dose (i.e., the amount of radiation received) to a construction worker placing road base containing PG is ~22 millirem per year (mrem/yr) or a 110 mrem total dose during the period that the worker is exposed (22 mrem/yr times five years for the total use dose).[10] The definitions of dose, mrem, and other technical terms are set forth in Appendices 1 and 2). A dose of 110 mrem corresponds approximately to a cancer risk of 5 in 100,000 (or 0.5 in 10,000, to use the same units as EPA's PG risk management safe level). Most actual exposures are less than those received by the RME and hence the associated risk would also be lower. The risk to the RME is significantly less than EPA's cancer risk limit of 3 in 10,000 during the alternative PG uses. Thus, consistent with the requirement in EPA's alternative PG use guidance (*Applying to EPA for Approval of Other Uses of Phosphogypsum: Preparing and Submitting a Complete Petition under 40 CFR 61.206*),[11] the use of PG in road construction is at least as protective as placement of phosphogypsum in a stack.

This Petition for PG reuse in road construction (and, therefore, any EPA approval) applies solely to paved roads; unpaved roads have not been evaluated and are not the subject of this Petition. PG containing average radiation levels equal to or lower than 148 pCi/g meets EPA's risk management safe risk level of 3 in 10,000 and, therefore, such PG may be safely used as road construction material. The risk assessment submitted with this Petition used a nominal average 27 picocuries per gram (pCi/g) which corresponds to a construction worker risk of 0.5 in 10,000.

TFI members measured the radioactivity level in the PG from some of their stacks. A summary of this data will be provided to EPA to support this Petition in a separate report. In summary, results to date reflect that average radiation levels from the composite samples taken from stacks

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[10] The risk assessment performed in support of this Petition used a nominal average radium -226 concentration of 27 picocuries per gram (pCi/g). The estimated risk from average radium -226 concentrations greater than 27 pCi/g can be scaled linearly from the road construction work risk (Appendix 2) (i.e., if an average radioactivity level of 27 pCi/g corresponds to 0.5 in 10,000 risk, then the EPA risk management limit of 3 in 10,000 corresponds to a radioactivity level of 148 pCi/g). The variation in the average radioactivity levels in the PG demonstrates that it is exceedingly unlikely that any randomly selected amount of PG will have an average radium-226 concentration above 27 pCi/g and thus, exceedingly unlikely that use of PG in road construction would result in a risk exceeding 3 in 10,000. The Petition seeks approval of up to an average of 35 pCi/g because this level represents the highest average level identified in prior testing by EPA.

[11] EPA PG Workbook, *supra* note 5, at 13.

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do not exceed the nominal radioactivity level used in the risk analysis (i.e., 27 pCi /g) and, more importantly, 148 pCi/g, the radioactivity level that corresponds to 3 in 10,000 risk management level that EPA has designated as safe.[12]

B. Process Used To Develop the Petition

TFI's Petition and supporting risk analysis were developed by reviewing the EPA PG Workbook and prior Petitions, and through a series of working meetings with EPA staff to obtain EPA input and direction on key elements of the analysis. Throughout this process, the methodologies and technical issues utilized in the technical evaluations benefited from EPA's input. The complete analysis for PG reuse in road construction, including methodologies and other aspects, is provided in this Petition and attached appendices.

C. Specific Requirements for a Petition

40 CFR § 61.206 requires that a Petition include the following:

- A submission in writing.
- The name and address of the person(s) making the request.
- A description of the proposed use, including any handling and processing that the phosphogypsum will undergo.
- The location of each facility, including suite and/or building number, street, city, county, state, and zip code, where any use, handling, or processing of the phosphogypsum will take place.
- The mailing address of each facility where any use, handling, or processing of the phosphogypsum will take place, if different from paragraph (b) (3) of this section.
- The quantity of phosphogypsum to be used by each facility.
- The average concentration of radium-226 in the phosphogypsum to be used.
- A description of any measures which will be taken to prevent the uncontrolled release of phosphogypsum into the environment.
- An estimate of the maximum individual risk, risk distribution, and incidence associated with the proposed use, including the ultimate disposition of the phosphogypsum or any product in which the phosphogypsum is incorporated.
- A description of the intended disposition of any unused phosphogypsum.

[12] A more detailed interpretation of the data will be provided in a separate submission to EPA.

- The Petition must be "signed and dated by a corporate officer or public official in charge of the facility."

Since multiple companies that own and operate PG stacks are making this request, this Petition was prepared and submitted to EPA by TFI on behalf of its members. A representative of TFI is included on the signature page.

The rule provides that the Petition include the "location of each facility, including suite and/or building number, street, city, county, state, and zip code, where any use, handling, or processing occurs." TFI believes this requirement can be satisfied in a two-step process in this case.[13]

> **Step 1** constitutes the first part of the approval process; submission of the Petition and EPA's determination that a particular use of PG is no less protective than storing it in stacks.[14]
>
> **Step 2** constitutes the notice to EPA of intent to use PG consistent with the Step 1 determination, including location and other required information. This occurs when a local, state or federal transportation entity (or its contractors) decides to utilize PG on specific road construction projects.

No sampling is required for the reasons discussed below.

IV. REGULATORY HISTORY AND CHANGING CONDITIONS

A. Regulatory History

1. The Original 1989 NESHAP Rule

Prior to 1989, PG in the United States was used for beneficial purposes, such as constructing roadways and agricultural soil amendments. The 1989 NESHAP rule required that all PG must be placed in engineered above ground impoundments (commonly referred to as "gypstacks") or in phosphate mines where it can be used as backfill. 40 CFR § 61.202. EPA's 1989 regulatory analysis was based on an estimate of 66 stacks located in 12 states with two-thirds located in Florida, Texas, Illinois, and Louisiana.[15]

2. Post-1989 Regulatory Developments

In 1992, in response to TFI's petition for reconsideration, EPA approved the use of PG as an agricultural soil amendment as long as the average concentration of radium-226 in the PG does

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[13] 40 C.F.R. § 61.201(a) addresses the approval of new uses and provides that PG may not be removed from stacks for any new use "without prior approval." Subsection (b) details the information that a petitioner must submit.

[14] There are practical reasons for pursuing this approach and there are no risks to EPA. First, in this case, neither TFI nor its members will know with certainty at the time a Petition is filed the actual location of the use. Notice of a project location prior to an EPA determination is unworkable in practice since it would expect potential users to request to use a product in a manner not permitted by law at the time of the statement. Second, there is no risk to EPA or the public because no newly approved use will be implemented without notice to EPA with the location and other information.

[15] 1989 Rule, *supra* note 2.

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not exceed 10 pCi/g (based on a maximum individual risk of 3 in 10,000 due to the use) and use of PG for research in amounts not to exceed 7,000 pounds. 40 CFR § 61.204-205.[16]

The regulations were also amended to allow EPA's Assistant Administrator of the Office of Air and Radiation (OAR) to approve, on a case-by-case basis, a new use if it is as protective of public health, in both the short and long term, as disposal in a stack or a mine. 40 CFR § 61.206(a)-(c).[17] In 1992, EPA rejected the use of PG in road construction based on an analysis that assumed a roadway constructed with PG might be abandoned in the future, with a home constructed directly on top of the abandoned roadway with no site preparation (i.e., mixing). This hypothetical scenario included several extreme assumptions that resulted in unrealistic levels of exposure.[18]

3. Prior Petitions

On December 22, 2004, EPA "conditionally" approved the Petition of the Florida Institute of Phosphate Research (FIPR) to use PG as cover material in a demonstration landfill test cell project (discussions with EPA on this project were initiated in 2002 and the petition submitted December 9, 2003).[19] PG, however, was never used as cover material in a landfill test cell. As TFI understands it, by the time the petition was approved, conditions had changed and the landfill owner withdrew its request.

In 2010, Louisiana State University prepared a proposal to allow the use of PG testing to determine if PG could be used to make coastal zone protection devices.[20] TFI's understanding is that this effort has been deferred for the time being.

These examples illustrate the unwieldiness of EPA's current approach to approvals for PG reuse. This has resulted in continued stacking, which has been subject to criticism as an unsustainable practice. Meanwhile, in most other countries, there are either few or no restrictions (allowing unrestricted use up to 27 pCi/g on PG reuse, or the radiation level restrictions do not limit use).

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[16] EPA, National Emission Standards for Hazardous Air Pollutants; National Emissions Standards for Radon Emissions from Phosphogypsum Stacks, 57 Fed. Reg. 23,305, at 23,309 and 23,311, 23,316 (June 3, 1992) (1992 Rule). The volume of PG was increased by a later amendment.

[17] *Id.* at 23,319.

[18] *Id.* at 23,312.

[19] Letter from Jeffrey R. Holmstead, Assistant Administrator of the Office of Air and Radiation, EPA to Michael Lloyd, Jr., Research Director Chemical Processing, Re: FIPR Petition (December 22, 2004).

[20] Louisiana State University, Preparation Of An Application For Approval To Use Stabilized Phosphogypsum As A Fill Material For Coastal Protection Devices, FINAL REPORT (prepared for Florida Institute Of Phosphate Research Institute, 2010).

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B. Factors Influencing Future Uses of PG

A number of factors influence the future uses of PG:

1. Current requirements to obtain regulatory approval prior to each individual new use slow the process of implementing beneficial, safe new uses. In many other countries, PG reuse is encouraged over storage and there are little or no regulatory restrictions on the use of PG up to an average radium content of 35 pCi/g, a level consistent with EPA's assessments of safe exposure.[21]

2. The size, costs and complexity of gypstacks have increased beyond original expectations. When the stacking solution was developed, two key factors were not fully recognized: (1) the significant volume of PG material that would be involved over time for storage in stacks, and (2) the beneficial reuses for which PG could safely be employed. Today, active stacks are concentrated in Florida, Idaho, Louisiana, and North Carolina and contain at least 1.7 billion tons of stored PG. EPA's final rule did not anticipate the significant increase in production that would occur, creating a need for new storage capacity at the rate of 30 million tons per year. As a result, EPA's 1989 final rule and its underlying analysis are not consistent with the environmental impact and cost of long-term stack storage on a scale compatible with modern fertilizer production facilities.

3. New data are available on the average level of radiation in gypstacks. Historically, EPA considered the radium-226 concentrations in phosphogypsum as ranging from 1.4 to 46 pCi/g.[22] At EPA's request, TFI members performed radiation sampling on gypstacks across the U.S. to provide updated information. Multiple stacks owned and operated by three companies were sampled. Up to approximately ten samples per stack were taken. The data reviewed to date demonstrates that the average radioactivity level for each stack is significantly lower than the 27 pCi/g used in the risk assessment (i.e., less than 0.5 in 10,000).[23]

4. The scientific community has developed an updated understanding of relative risks associated with PG.[24] This Petition has been prepared to enable EPA's regulatory decision to be based on the current, best scientific understanding of

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[21] International Fertilizer Industry Association, Phosphogypsum: Sustainable Management and Use at Chapter 5, 52-63 (2016) (IFIA Sustainable PG Management Report), which reviews international and U.S. roads constructed with PG. Other chapters address other uses.

[22] EPA 1992 BID, *supra* note 7.

[23] The Risk Assessment found that the nominal level of radium-226 assumed for calculation purposes to be contained in PG (27 pCi/g) corresponds to a maximum risk of 0.5 in 10,000. Thus, the EPA PG risk management limit of 3 in 10,000 corresponds to a level of 148 pCi/g in PG (using the non-rounded risk for the construction worker). Therefore, PG may be safely used as road construction material. The Risk Assessment submitted with Petition used a nominal average 27 picocuries per gram (pCi/g) which corresponds to a construction worker risk of 0.5 in 10,000.

[24] *See* International Atomic Energy Agency (IAEA), Radiation Protection and Management of NORM Residues in the Phosphate Industry, Safety Reports Series No. 78 (2013), *available at* https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1582_web.pdf.

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radiation protection and management related to PG reuse. The International Atomic Energy Agency (IAEA), an international organization which the U.S. helped establish to provide a scientific source of recommendations on radiation issues, has determined that radionuclide activity concentrations in PG material are less than 1 Bq per gram (Bq/g) (which corresponds to 27 pCi/g) "implying that it is not necessary to regulate."[25] Section IV below summarizes this updated understanding. U.S. and international research, as well as data from uses in developed nations, are now available to support various PG uses and demonstrate that PG reuse is at least as protective of public health as storage in stacks. More than a dozen beneficial uses have been analyzed worldwide, resulting in significant, successful PG reuse applications in at least 21 countries.[26]

Further, U.S. risk assessment approaches have changed based on experience and evolving environmental management policies since the 1980s, along with increased awareness of product lifecycles and sustainability. These changed conditions enable a more thorough and appropriate evaluation of PG reuse in road construction, and a demonstration that this reuse is protective of human health and the environment.

5. EPA policies encourage reuse and recovery of high-volume, low-risk waste. EPA's 1989[27] and 1992[28] risk management decisions concerning PG reuses acknowledge, but do not provide, an effective mechanism to implement PG reuse decisions that are consistent with the Agency's overarching policy of supporting recycling. Since 1992, EPA has increased its emphasis on understanding product lifecycles and has adopted sustainability policies and encouraged sustainable practices.

6. The economics of gypstacks have changed. The cost to stack and manage gypstacks is increasing. These rising costs are a concern to phosphate fertilizer producers that must maintain a competitive advantage in a global marketplace. Fertilizer companies outside the U.S. may reuse their PG material safely utilizing the IAEA standards. This puts U.S. companies at a significant economic disadvantage. The international community has actively moved in the direction of safe PG use and recycling, creating an increasing competitive disadvantage for U.S. industry, particularly when one considers the costs associated with gypstack maintenance, closure, and long term care.

7. Perceptions of gypstacks have changed. EPA's final rule did not anticipate a range of public sentiment regarding the long-term presence of gypstacks. Inactive stacks that are already closed (or in closure) exist in various locations. There are also concerns about long-term gypstack aesthetics. Some local governments and

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[25] *Id.* at 56. This statement does not in any way preclude a risk based determination that higher levels might also be acceptable.

[26] IFIA Sustainable PG Management Report, *supra* note 21.

[27] EPA, Comments and Response to Comments, NESHAP, National Emission Standards for Radon Emissions from Phosphogypsum Stacks at 3, EPA-402-R-98-007 (1998).

[28] 1992 Rule, *supra* note 16, at 23,306.

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communities have expressed a preference for reuse of PG in a manner that encourages redevelopment,[29] because such reuse increases economic development by generating jobs associated with the transportation and reuse of PG, and frees up land for other uses.

8. It should be noted that TFI's proposal represents a significant regulatory burden reduction that will create new commercial markets, industries and jobs. This is in the context of the dramatic increase in PG use worldwide since 2008, from a baseline of close to zero to 35-40 million tons consumed worldwide by 2015.[30] To make comparable advancements, the U.S. phosphate industry, led by TFI's Petition, requests approval for certain PG reuses. If successful, approval would support the industry's sustainable development goals by expanding the list of PG beneficial uses and ameliorate substantial, avoidable regulatory burdens and costs imposed by the NESHAP Subpart R regulations.

With this background in mind, Section V summarizes the Risk Analysis and metals screening evaluation that have been completed (see Appendices 2 and 3) and demonstrate the safety of PG reuse in road construction. Key exposure and risk calculations and application of EPA's risk management criteria are described. The complete exposure and risk analyses are provided in appendices to this Petition.

V. SUMMARY OF THE EVALUATIONS CONDUCTED FOR THE PETITION

A. Overview

The Petition process is governed by EPA's document, titled "Applying to EPA for Approval of Other Uses of Phosphogypsum: Preparing and Submitting a Complete Petition under 40 CFR 61.206, A Workbook" (EPA PG Workbook).[31] The key requirement expressed in this guidance is that in responding to any proposed petition, EPA must decide whether the radiological risk associated with the alternative use poses no greater risk than placement in stacks.[32]

The decision concerning whether the radionuclide risk associated with PG in alternative uses is acceptable depends upon many risk analysis elements, including:

- The specific exposure scenarios that are determined to be appropriate. This Petition seeks approval of the use of PG in road construction based on a risk analysis for a series of specific exposure scenarios;

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[29] *See e.g., EPA holds meeting about Mississippi Phosphate Site*, St. Louis Post-Dispatch, Jan. 11, 2018, *available at* https://www.stltoday.com/news/world/epa-holds-meeting-about-mississippi-phosphate-site/html_0a41c1fa-96ef-54bb-a825-8fcacb4b4463.html (comment of Pasagoula Mayor, Dane Maxwell, at an EPA public meeting regarding the Mississippi Phosphate site cleanup: "We want it clear and ready for development as soon as possible").

[30] *See* IFIA Sustainable PG Management Report, *supra* note 21.

[31] EPA PG Workbook, *supra* note 5, at 13.

[32] *Id.* at 12.

- The RME exposure assumptions or parameters that are selected to estimate a high end radiation dose estimate during the alternative use of PG, i.e., an assumption likely to overestimate exposure. This Petition developed RME exposure assumptions for each exposure scenario and receptor and calculated a high end RME dose;

- The radiation dose (see text box, above) to risk conversion factor used;

- The cancer risk estimate based on RME exposure assumptions and the radiation dose to risk conversion factor of 5 in 10 million mrem;

- EPA's cancer risk limit for new PG uses of 3 in 10,000 during the use;

- A comparison of the estimated cancer risk to EPA's risk limit for new PG uses; and

- EPA's Risk Management Decision considering economic and other risk management factors.

EPA did not assess chemical risk in its 1992 risk assessment and review of new uses, including agricultural uses.[33] Thus, petition development and consideration by EPA are primarily focused on exposure analyses associated with radiological risks from the proposed new use. For this Petition, EPA requested that TFI perform a screening level evaluation for chemical risks (i.e., metals). It should be noted that PG contains naturally-occurring radioactivity and metals. This chemical risk screening is provided as a supplement to the radiological risk assessment (Appendix 3).

B. Exposure Scenarios

1. Overview

PG reuse was considered for road construction. This led to the development of the following RME exposure scenarios evaluated in the risk assessment:

- Road Construction Worker who builds roads exclusively with PG material for five years;

- Road User who routinely commutes on the constructed roadway by vehicle, motorcycle or bicycle for 26 years (motorist/bicyclist was deemed most conservative);

- Nearby Resident who lives in a home located 50 feet or more from a PG roadway for 26 years. To illustrate the amount of exposure reduction with distance, exposure to a resident who resides 20 feet from the PG roadway for 26 years was also calculated;

[33] EPA 1992 BID, *supra* note 7. 1992 Rule, *supra* note 16, at 23,305.

- Truck Driver who delivers PG for road base material to a construction site for five years; and

- Utility Worker who excavates across a PG roadway during utility maintenance projects and is exposed in a trench for 160 hours in a year.

These exposure scenarios were selected based on a review of prior regulatory submissions as well as discussions with EPA personnel, and the best professional judgment of the scientists assisting in the preparation of the Petition.[34] This analysis includes receptors added at EPA's request during the working sessions to fully evaluate public health.

This Petition also includes, at EPA's request, a hypothetical future "Reclaimer" scenario which the risk analysis concludes is an extreme exposure (Extreme Reclaimer), i.e., the exposure is much higher than a RME exposure scenario. This scenario, therefore, should not be utilized to determine if the risk from the use of PG in the construction of roads meets the EPA risk management limit of 3 in 10,000.

In TFI's view, the design and construction of roadways will be governed by policies and constraints on future land use associated with public infrastructure. In light of this, the reclaimer scenario of building a house on top of an abandoned roadway is not a reasonably anticipated future land use. Nevertheless, at EPA's request, this report separately assesses the risk of this hypothetical scenario.

2. **Reasonable Maximum Exposure (RME)**

In order for there to be a risk, there must be exposure. EPA uses an RME metric to assess exposure risk. The "intent of the RME is to estimate a conservative exposure case (i.e., well above the average case) that is still within the range of possible exposures."[35] Each exposure factor used to estimate the RME should be selected "so that the resulting estimate of exposure is consistent with the higher end of the range of plausible exposures" (citing EPA's 1991 guidance).[36]

A National Academy of Science (NAS) Committee reviewing EPA's regulation of technologically enhanced naturally occurring radioactive material (TENORM) recommended

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[34] Arcadis (a firm specializing in design and consultancy for natural and built assets) and Exponent (an engineering and scientific consulting firm).

[35] EPA, EPA: Risk Assessment Guidance for Superfund: Volume III - Part A, Process for Conducting Probabilistic Risk Assessment, 7-1 (2001), *available at* https://www.epa.gov/sites/production/files/2015-09/documents/rags3adt_complete.pdf (EPA Risk Assesment Guidance for Superfund). *See also* Interstate Technology Regulatory Council, Decision Making at Contaminated Sites, Issues and Options in Human Health Risk Assessment at 6.1.1 (2015), *available at* https://www.itrcweb.org/risk-3/Default.htm#6.%20Exposure%20Assessment.htm#6.1__Determining_Appropriate_Exposure_Factors%3FTocPath%3D6.%2520Exposure%2520Assessment%7C6.1%2520%2520Determining%2520Appropriate%2520Exposure%2520Factors%2520%7C_____0 (ITRC, Decision Making at Contaminated Sites), citing EPA Guidance, which states that "[t]he RME . . . can be defined as 'the maximum exposure that is reasonably expected to occur within a potentially exposed population.'"

[36] *Id.*

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that EPA "should use exposure and dose risk assessments that are 'reasonably realistic'" in developing standards for exposure to the various types of low level naturally occurring radiation.[37] "The Committee defined 'reasonably realistic' as 'not....intended to greatly overestimate or underestimate actual effects for the exposure situation of concern,'" and EPA agreed with the Committee's recommendations.[38]

The exposure calculations in the Petition use currently accepted radiation modeling methods such as RESRAD and MicroShield. State regulators, citing to EPA guidance, note that "if high-end values are chosen for every exposure factor, then the resulting exposure estimate may no longer be consistent with the RME and may exceed the realm of possibility altogether."[39]

The use of reasonable exposure assumptions is supported by the courts, which have long held that exposure assumptions "must bear some rational relationship" to actual conditions, and disallowed unduly conservative approaches. For example, a court rejected EPA's use of an extreme assumption - that a child eats sludge applied to roadside cemeteries every day for a five year period.[40]

Scenario-specific exposure assumptions were selected for this analysis in accordance with EPA guidance and methodology (see Table 1 below). These exposure assumptions are contained in appendices and accompanied by detailed scientific support, citations to guidance, discussion of best professional judgment and prior precedent used to make the selections. A summary of key exposure assumptions is provided in Table 1 below.

Table 1: Summary of Key Exposure Assumptions

Person	Description	Years	Model	Rationale
RME Scenarios				
Road Worker	Builds roads exclusively with PG material	5	RESRAD	The worker who uses PG to build a road is closest to the PG mixtures in road base and/or paving. Used Florida Department of Transportation construction project data and EPA guidance.
Truck Driver	Delivers PG to the construction site to be used in road base and/or paving materials	5	MicroShield	A truck driver hauls PG to the road construction site for 5 years (the truck body provides some shielding).
Nearby Resident	Resident lives in a home located 50 feet or more from	26	MicroShield	EPA guidance on exposure values. To illustrate the amount of exposure

[37] EPA, Report to Congress, Evaluation of EPA's Guidelines for Exposures to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), 15 (June 2000) (describing a National Academy of Sciences report on TENORM), *available at* https://www.epa.gov/sites/production/files/2015-04/documents/402-r-00-001.pdf (EPA Report to Congress Re: TENORM).

[38] *Id.*

[39] ITRC, Decision Making at Contaminated Sites, *supra* note 35, at 6.1.1.

[40] *Leather Indus. of America v. EPA*, 40 F.3d 392, 405 (D.C. Cir. 1994).

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	a road			reduction with distance, exposure to a resident who resides 20 feet from the PG roadway for 26 years was also calculated.
Road User	Resident drives on the road in a vehicle, or on a motorcycle or bicycle (the motorist/bicyclist is evaluated as the most conservative)	26	RESRAD	EPA guidance on exposure values.
Utility Worker	Worker in trench dug across a PG roadway (e.g., utility work)	160 days	MicroShield	Best professional judgment, based, in part, on limited time trenching occurs (since, among other reasons, it obstructs traffic).

At EPA's request, the Petitioner provided a "reclaimer scenario" (an assessment of the extreme hypothetical exposure if the road is abandoned and a house is constructed on the abandoned roadbed (see Table 2)).

Table 2: Reclaimer Scenario Exposure Assumption

Hypothetical Extreme Exposure Reclaimer Use Scenario				
Reclaimer Resident	Home constructed on an abandoned road	26	RESRAD (for gamma) Spreadsheet for radon	The abandonment of a road and construction of residential housing at the location is an extremely unlikely event included to evaluate the lifecycle and ultimate disposition of a PG road and is not a RME exposure

The RME is used to calculate the dose (i.e., the amount of radiation that the individual in the exposure scenario receives over a particular unit of time.) In our situation, the annual and total doses depend on the length of time exposure occurs for that exposure scenario. Different exposure scenarios have different lengths of exposure. Risk is assumed to increase in direct proportion to the RME dose (i.e., if the RME dose increases by a factor of two, the risk increases by a factor of two).

The risk is then compared to the EPA risk management levels. EPA has long utilized (and courts have long upheld) the principle that a 1 in 10,000 risk level is "safe." As a unanimous *en banc* ruling of the Court of Appeals for the District of Columbia Circuit candidly noted, the basis for claiming harm from exposure to chemicals at extremely low environmental levels is more a function of "the rules of arithmetic rather than because of any knowledge" and there was "no particular reason to think that the actual line of the incidence of harm is represented" by the assumption selected by EPA.[41]

This acknowledgment is also apt for the risks from radionuclides. EPA's guidance for new uses of PG states unequivocally that for new PG uses to be approved, petitioners must demonstrate

[41] *Natural Resources Defense Council, Inc. v. U.S. EPA*, 824 F.2d 1146, 1165 (D.C. Cir. 1987).

that the cancer risk to those exposed to phosphogypsum as a result of proposed reuse "must not be more than three in ten thousand (3×10^{-4}, i.e., 3 in 10,000").[42] In the radionuclides NESHAP, EPA primarily, but not exclusively, evaluated the maximum individual risk (MIR) (which is the added chance of a cancer) and compared it to the NESHAP risk management level of 3 in 10,000.[43]

The use of the 3 in 10,000 "risk threshold is consistent with the determination of a 'safe' level first announced in the NESHAP for certain benzene source categories (54 FR 38044, September 13, 1989)."[44] As noted above, in the 1989 radionuclide rulemaking, EPA determined that six radionuclide source industries presented a cancer risk higher than 1 in 10,000 but that nonetheless was "essentially equivalent" to EPA's safe risk level "in light of the numerous uncertainties."[45] Similarly, EPA reaffirmed in 1992 that a 3 in 10,000 risk level was protective of human health and consistent with EPA's long-standing risk management goals.[46] In particular, EPA "determined" that the 3 in 10,000 risk level provided "an ample margin of safety, considering the cost, scientific uncertainty, and technological feasibility of control technologies needed to further reduce the radon emissions from [the PG] stacks."[47]

In summary, EPA explicitly has determined that the 3 in 10,000 cancer risk for radionuclides (including PG) is safe, consistent with overall EPA risk management policy. EPA has concluded that the "proposed other use will not cause a threat to the public or environment greater than if the phosphogypsum were stored in the stack," if the risk is not "more than three in ten thousand [3 in 10,000]."[48]

The relationship between exposure dose and risk is further elaborated on in Appendices 1 and 2.

C. ICRP Dose to Risk Relationship

The risk assessment selected in this Petition is the ICRP dose to risk conversion factor. The ICRP sets out the basis for evaluating health effects from radiological exposure along with recommendations for using specific values for regulatory purposes. While there are broad uncertainty bounds at low-dose exposures, the assumption of a linear relationship between exposure and risk is maintained regardless of the possibility of a threshold below which there is

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[42] EPA PG Workbook, *supra* note 5, at 13.

[43] 1989 Rule, *supra* note 2, at 51,654, 51,659, 51,660. In this context, the risk distribution (i.e. the range of risks to which the population is exposed) decreases as distance to the road increases, for PG use in road construction. Relatively quickly the dose falls below the dose that corresponds to background. The exposure to the residents is below the 3 in 10,000 safe level.

[44] EPA PG Workbook, *supra* note 5, at 5.

[45] 1989 Rule, *supra* note 2, at 51,654, 51,664, 51,666, 51,668-69, 51,669, 51,677, 51,682 risks ranged between 1 in 10,000 and 3 in 10,000. *Id.*

[46] 1992 Rule, *supra* note 16, at 23,305, 23,311-12, 23,316.

[47] EPA PG Workbook, *supra* note 5, at 5.

[48] *Id.* at 13.

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no risk. In Publication 103, ICRP provides an analysis of the exposure values considered in that analysis. On the basis of model uncertainty and epidemiological evidence, the ICRP recommends a dose-to-risk coefficient of 5% per Sievert. (one Sievert is equivalent to 100 rems or 100,000 mrem, see explanation of terms text box, above).[49] This coefficient is the basis for current international radiation safety standards, and is considered by ICRP to be "appropriate for the purposes of radiological protection." Although it is based on cancer mortality as the endpoint, it is also approximate for all calculated detrimental effects.

For our risk analysis, we use a dose conversion expressed in terms of millirems or mrem.[50] Translating the 5% risk per Sievert recommended by the ICRP for regulatory purposes yields 5 x 10^{-7} risk per mrem.

The risk assessment submitted as part of this Petition estimates the annual dose for each of the exposure scenarios, summed over the associated years of exposure, to provide a total dose that is then converted to a cancer risk using a dose-to-risk conversion factor of $5x10^{-7}$ risk per mrem (i.e., 5/10,000,000).

Our use of 5 x 10^{-7} as a conversion factor is consistent with EPA risk assessment procedures.[51] The EPA's 2011 guidance provides cancer risk factors for uniform whole-body exposures of low-dose gamma radiation to the entire population, and reports an estimated 90% confidence interval for cancer mortality of 2.8% to 10% per Gy[52] (i.e., from 2.8 x 10^{-7} to 10 x 10^{-7} per mrem).[53] This range is essentially the same dose to risk conversion range derived by ICRP.

The value we use is also consistent with the perspective of the National Council on Radiation Protection and Measurements (NCRP) (the U.S. organization chartered by the U.S. Congress in 1964 to, among other things, "develop … recommendations about …protection against radiation" (i.e., NCRP uses the same dose to risk conversion factor as in the 2007 ICRP)).[54]

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[49] ICRP, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, 55, 87 (March 2007).

[50] The mrem is a common unit of radiation dose. In this report, "dose" refers to effective dose, which simply means that when a person is exposed to a uniform radiation (e.g., external gamma radiation), all of the doses to the different organs are weighted by their radiosensitivity and added together. See Appendices 1 and 2 for more detailed discussion of the definitions and application of these factors.

[51] Similarly, the international community has widely adopted the International Atomic Energy Agency (IAEA) determination that 1 millisievert (1 mSv) per year is the acceptable level of radiation exposure (for example, the European Union [EU] regulations). *See* Radiation Protection and Management of NORM Residues in the Phosphate industry, *supra* note 24, at 165.The IAEA and EU determinations are also based on the International Commission on Radiological Protection, The 2007 Recommendations of the International Commission on Radiological Protection, *supra* note 49, at 55, 97 Table 5, 116 Table 8.

[52] For practical purposes as to gamma radiation, 1 Gy = 1 Sv = 100 rem = 100,000 mrem.

[53] EPA, EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population, EPA 402-R-11-001 (April 2011).

[54] National Council on Radiation Protection and Measurements, Management of Exposure to Ionizing Radiation: Radiation Protection Guidance for the United States, NCRP Report No. 180, 42 (December 2018).

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The ICRP analysis was also relied upon by the European Union (EU) in selecting its general population acceptable dose level.[55] The EU appointed a group of experts to provide advice on the basic safety standards, taking into account the 2007 recommendations of the ICRP (specifically, ICRP Publication 103 since the ICRP reflected "new scientific evidence and operational experience.)"[56]

The most recent report of the NCRP (2018) (Report No. 180) provides a detailed discussion of the risks from exposure to ionizing radiation and states that "*[t]he value of 5 % Sv*$^{-1}$ [i.e., 5/10,000,000 per mrem] *is a rounded value for radiation detriment used to inform all the NCRP recommendations regarding stochastic effects,*"[57] (emphasis added).

In summary, the use of the ICRP dose to risk relationship is scientifically sound and supported by many independent governmental entities, including EPA and NCRP. We elaborate further in Appendices 1 and 2. The "conservative" nature of the assumptions underlying the dose to risk relationship and associated uncertainties are discussed below.

For the reasons noted above, the risk estimates derived for PG using the ICRP dose to risk conversion factor are based on a linear relationship between dose and risk for the very low dose exposures derived for this report. Therefore, they are appropriate for use in the Petition and can be relied upon by EPA in its decision making.

D. Calculation of Risk that Corresponds to the RME

This section summarizes the RME doses calculated in the Risk Assessment and explains generally how they are derived.

1. Deriving Dose for the Period of Use

A dose is the cumulative amount of radioactivity absorbed (weighted to take into account the different medical impacts of different types of radiation). The dose is calculated using the RME associated with each scenario.

Duration is specific to the exposure scenario. For a resident, the exposure period is 26 years based on standard EPA guidance.[58] For a road construction worker, the length of exposure is

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[55] ICRP is an international expert advisory body that offers its recommendations to regulatory and advisory agencies, mainly by providing guidance on the fundamental principles on which appropriate radiological protection is based. The 2007 recommendation was produced "after eight years of discussions, involving scientists, regulators, and users all around the world." The 2007 Recommendations of the International Commission on Radiological Protection, *supra* note 49, at 3.

[56] Official Journal of the European Union, Council Directive 2013/59/Euratom, 5 (Dec. 5, 2013), *available at* http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2014:013:FULL&from=EN. L 13/2 COUNCIL DIRECTIVE 2013/59/EURATOM (laying down basic safety standards for protection against the dangers arising from exposure to ionizing radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom) (Council Directive 2013/59/Euratom).

[57] National Council on Radiation Protection and Measurements, Management of Exposure to Ionizing Radiation: Radiation Protection Guidance for the United States, NCRP Report No. 180, 42 (December 2018).

five years based on data from roadway construction projects and EPA guidance. The risk assessment determined that the 3 in 10,000 risk level corresponded to a total cumulative dose of 600 mrem and this value can be used to judge the magnitudes of exposure for each scenario. Table 2 below summarizes the exposure doses calculated in the risk assessment on an annual and scenario basis.

Table 3: Total Dose Summary

Person Exposed	Annual Dose	Years	Total Use Exposure Dose
Road Worker	22 mrem	5	110
Truck Driver	18.6 mrem	5	93
Nearby Resident	multiple exposures over 26 years	26	16
Road User	1 mrem	26	28
Utility Worker	0.8	160 hours in 1 year	0.8

2. **Converting the Total Use Dose to Risk**

Radiation risk for cancer is calculated as the product of the RME exposure dose for each scenario and the dose-to-risk conversion factor. The distance from the road and durations of exposure are key considerations in calculating the total dose risk. While the RME is designed to bound these, most residents would be located at greater distances from the road and/or experience shorter durations of exposure than the RME individual. Thus, actual doses for the populations would be less than those presented here.

As noted above, using a dose-to-risk conversion factor of $5x10^{-7}$ risk per mrem, 600 mrem corresponds to a 3 in 10,000 risk level. From this relationship, one can calculate the risk for a particular dose. The result of the risk calculations are summarized in Table 3 below. The results of the calculations are provided in Appendices 1 and 2 of this Petition.

Table 4: Total Use Dose and Risk Table Compared to Background

RME Exposure Scenario	Total Use Dose (mrem)	Years	Risk From the Use
Road Construction Worker	110	5	0.5 in 10,000
Truck Driver	93	5	0.5 in 10,000
Road User	28	26	0.1 in 10,000
Nearby Resident	16	26	0.08 in 10,000
Utility Worker	0.8	160 hours in 1 year	0.004 in 10,000

3. **Road Construction Worker Risk**

Based on the assessments provided in this Petition, the highest estimated RME exposure is for the road construction worker placing road base containing PG that contains radium -226 at 27

[58] 26 year exposure duration for residence – 90th percentile recommended by EPA. EPA, Human Helath Evaluation Manual, Supplemental Guidance: Update of Standard Default Exposure Factors, OSWER Directive 9200.1-120 (Feb. 6, 2014) and EPA, Exposure Factors Handbook, EPA/600/R-09/052F (2011).

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picocuries per gram. The exposure dose amounts to ~22 mrem/year (which results in a 110 mrem total dose for the exposure period of five years). This dose corresponds approximately to an incremental cancer risk of 0.5 in 10,000, which is over 5 times less than the PG use risk management level of 3 in 10,000.

4. **Risk to the Nearby Resident**

In addition to the highest risk individual (a road construction worker), the risk assessment also evaluated the exposure doses and risk to local residents who may live immediately adjacent to the road. Consideration was given to all stages of life from childhood through adult. Exposure depends on distance, with exposures dropping off quickly as distance from the road increases. Nevertheless, for people living immediately adjacent to the road, the exposures and risks are well below the risk management level of 3 in 10,000.

The exposure doses and risks were estimated without considering shielding during the period of construction; shielding was included when estimating doses following construction of the road. Shielding of residents was afforded by the road surface as well as by embankments and other structures that cover the sides of the road base.

The cumulative incremental dose associated with living in a house adjacent to a road with a PG base is 16 mrem and the associated risk is 0.08 in 10,000. These RME exposure dose and risk estimates to nearby residents are well below the EPA risk management levels.

5. **RME Risk from the Other Exposure Scenarios**

Doses and associated risks for all other RME exposure scenarios (the truck driver delivering the PG, the users of the road, and the utility worker in a trench near the road) are lower than those for the road construction worker (see Table 3).

6. **RME Exposures/Risks, by Definition, are the Highest Exposures**

All exposure scenarios have doses and risks that are less than the EPA's risk management levels. The RME risks are constructed to overestimate rather than underestimate the actual risks and this provides confidence for making decisions that are health protective.

Other workers who are more distant from the PG have lower exposures than the construction worker (and, therefore, lower risk). Similarly, most residents living near roadways are exposed to lower risk levels and most PG will contain lower radiation levels used in this calculation. Moreover, the dominant source of dose is gamma radiation which decreases with distance and hence, residents who live more than 50 feet from a road will receive a lower dose (and consequent risk) than the RME at a distance of 50 feet from the edge of the road.

7. **Comparison to Background**

Because radiation is always present naturally, it is helpful to compare the incremental radiological exposures to background levels to provide perspective. While natural background varies geographically (between states and even within states), a value of approximately 310 mrem a year was used for comparison because it is a widely used national background level. Background radiation varies naturally from ~100 mrem to 1,000 mrem. Thus, the ratio of total

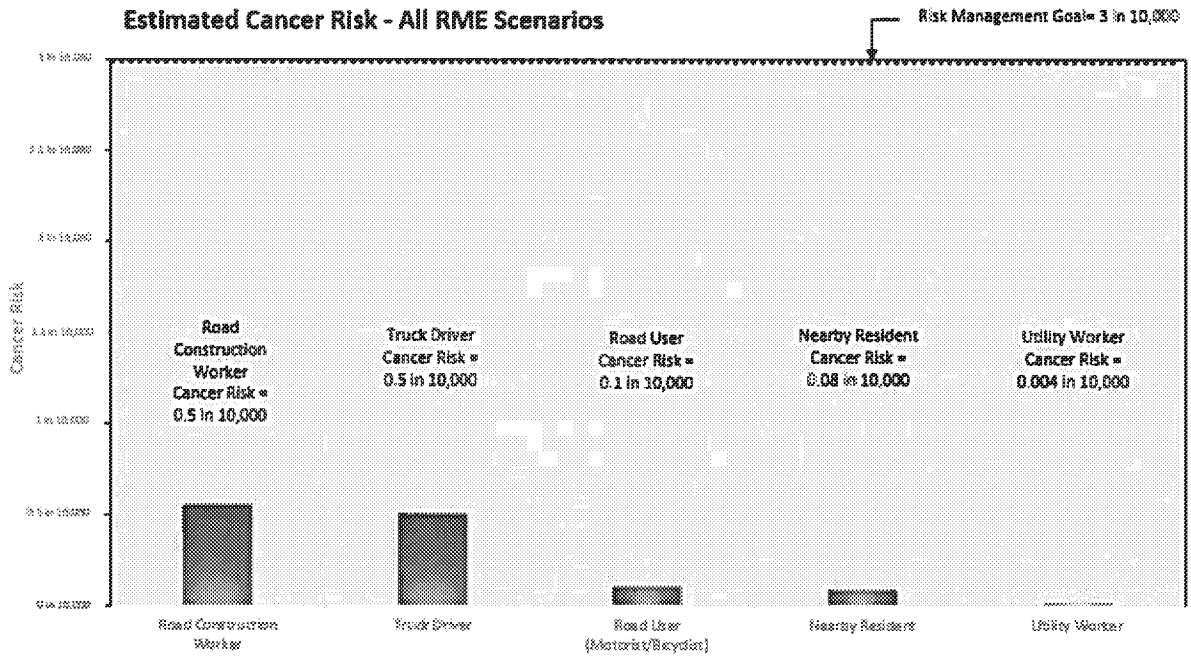
use exposure to background will vary depending upon the location of the road (see Table 4 below). Given the conservative nature of the exposure estimates, these incremental exposures would likely be within the variability of measurement for ambient radiation.

Table 5: Dose, Risk, and Background Summary for All RME Scenarios

Receptor	CSM	Exposure Duration (years)	Exposure Dose (mrem)	Estimated Cancer Risk	Background Dose from Exposure Duration (mrem)	Exposure Dose Percentage of Background Dose (%)
Reasonable Maximum Exposure Scenarios						
Road Construction Worker	PG in Road Base	5	110	0.5 in 10,000	1550	7%
Road User (Motorist/Bicyclist)	PG in Road Base & Surface	26	28	0.1 in 10,000	8060	0.3%
Truck Driver	PG-containing material for Road Base	5	93	0.5 in 10,000	1550	6%
Nearby Resident	PG in Road Base & Surface	26	16	0.08 in 10,000	8060	0.2%
Utility Worker	PG in Road Base	1	0.8	0.004 in 10,000	310	0.3%
	EPA Cancer Risk Management Goal		600	3 in 10,000	600	

Estimated cancer risk below this goal.

Figure 2: Estimated Cancer Risks



8. Disposition Scenario

The EPA PG use regulations require an assessment of the risk from the ultimate disposition of PG for any product in which the PG is incorporated.[59] The RME for the ultimate disposition of a

[59] 40 C.F.R. § 61.602.

new road constructed with PG is that it serves as an established part of municipal (county, state, or federal) infrastructure and as such would require periodic repair and expansion as needed.

All public roadways and associated rights of way are owned and operated by the government and are all subject to governmental jurisdiction with zoning and land use requirements that support continued roadway use. Maintaining public roadways and associated rights of way into the future is consistent with current trends in community plans to maintain and expand roadway infrastructure and utility services (buried within right of ways) and to provide access (e.g., ingress/egress to surrounding parcels). Converting a roadway to a residential property would complicate or eliminate access to surrounding parcels in addition to the redeveloped residential property and is not a realistic assumption.[60]

The sustainability of roads and reuse of road construction materials are key aspects of guidance and plans for roads under the jurisdiction of the Federal Highway Administration and state departments of transportation. The in-place abandonment of municipal infrastructure and allowance for construction of residences on top of these abandoned roads runs counter to sustainable infrastructure projects involving road construction.

Road maintenance activities include removing the surface, grinding and reusing or disposing of the materials consistent with federal, state, and local regulations. Exposures and risks associated with maintenance of roads and reuse of construction materials are expected to be comparable to or less than those detailed in the risk assessment for road construction.

E. Extreme Hypothetical Reclaimer Requested By EPA (> RME)

Our evaluation is that, in light of current policies and known constraints on future land use for public infrastructure, a hypothetical reclaimer scenario does not represent a reasonably foreseeable future use for inclusion in the risk analysis for this Petition.[61] Thus, a Reclaimer Exposure Scenario should not be utilized to determine whether to approve the use of PG for road construction.[62]

Since EPA requested that the risk analysis include the extreme hypothetical reclaimer scenario, it is summarized below. The annual total radiation dose is 3 mrem, which converts to 78 mrem

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[60] The determination that the reclaimer scenario is also not a reasonably anticipated future land use for public roadways is also supported by EPA policy published after the 1992 BID. EPA published its Superfund Land Use Directive in 1995 (EPA, Land Use in the CERCLA Remedy Selection Process, OSWER Directive No. 9355.7-04 (May 25, 1995)) and reaffirmed the policy in 2001 (EPA, Reuse Assessments: A Tool To Implement The Superfund Land Use Directive, OSWER 9355.7-06P (June 4, 2001)). EPA's Land Use Directive acknowledges that "EPA has been criticized for too often assuming that future use will be residential" and identifies several evaluation factors to identify reasonably anticipated future land use, such as current land use, zoning laws and maps, community master planning, population growth patterns and projections, accessibility to existing infrastructure, site location, federal/state land use designation, and others.

[61] Memorandum from TFI to Lee Veal, Director, Radiation Protection Division, U.S. Environmental Protection Agency (April 24, 2019). This detailed memorandum explains the reasons that the Reclaimer Exposure Scenario is not a RME.

[62] As a practical matter, if a risk assessment uses extreme enough assumptions, the calculated risk will exceed any risk management safe level. Thus, realistic but high end RME are used.

over 26 years (the total use dose). The resident reclaimer scenario requested by EPA is an extreme exposure duration. Nonetheless, this risk (which is higher than an RME risk) corresponds to about a 0.4 in 10,000 risk, still below the PG use risk management level of 3 in 10,000.

However, this hypothetical scenario can also be considered to be an extreme upper bound screening assessment. Even this extreme hypothetical scenario does not result in exposures and risks that exceed the EPA risk management level of 3 in 10,000. It must be emphasized that the use of the reclaimer scenario does not mean it is a foreseeable ultimate disposition. In any event, the fact that this extreme exposure scenario presents a risk below 3 in 10,000 demonstrates that any conceivable RME scenario related to ultimate disposition will meet the EPA's risk management level.

F. Groundwater Pathway Screening Analysis

EPA's PG Petition guidance suggests that the Petition should address other potential pathways of exposure, such as the ground water pathway, if they are relevant.[63] The Petition used a screening analysis to address these pathways and, where appropriate, referenced EPA's prior evaluations. A conservative screening level analysis generally is used to determine at an early stage that no further analysis is warranted.

G. Radionuclides in Groundwater

EPA performed extensive modeling of the likely migration of radionuclides in a 1992 assessment of the risk from PG used in agriculture and road construction. Neither concluded that the groundwater pathway supported restrictions on the use of PG.[64] EPA's risk assessment determined in 1992 that "no radionuclides are calculated to reach the onsite well via the groundwater pathway" nor are any "radionuclide calculated to reach the off-site river or well via groundwater."[65] The radionuclide risks were found to be zero. The TFI consultants agree with these prior assessments and no additional evaluation was deemed necessary. No monitoring data reviewed indicates a significant groundwater impact from radionuclides.

H. Screening Evaluation of the Potential Impact of Non- Radionuclides in PG

The EPA PG Guidance states:

> [A petitioner] "must provide information on the other toxic or hazardous constituents of the waste…to assure that the proposed use does not cause non-radiological risks to human health and the environment."[66]

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[63] EPA PG Workbook, *supra* note 5, at 10.

[64] EPA 1992 BID, *supra* note 7, at Chapter 4. See discussion in Appendix 2.

[65] *Id.*, at 4-31, 4-34, Scenario 8, Tables 4-5, 4-18, FN C, Scenario 11, among other sources.

[66] EPA PG Workbook, *supra* note 5, at 9.

> To the extent the phosphogypsum is land applied or will remain in place following the test, the risk assessment must examine other potential pathways of exposure, in particular with respect to ground-water and surface water. Consideration of multiple pathways, particularly pathways associated with ground water, are consistent with our review of alternative uses as found in the 1992 rulemaking on phosphogypsum.[67]

Despite this, EPA did not include an assessment of the impact of metals in its review of alternative uses of PG in 1989 or 1992 (see Appendix 3).

However, EPA requested that TFI perform screening analyses of the potential impact of direct contact with PG by road construction workers, and evaluate potential metals leaching on ground and surface water quality. Thus, these assessments were performed and appear in Appendix 3.

These analyses confirm that PG is "safe" for worker handling with respect to non-radionuclides as well. Road construction workers were assumed to come into direct contact with PG (incidental ingestion, inhalation, and dermal contact). The PG concentrations were then compared to health-based screening levels. The chemicals in PG were found to be either a low risk or present at background levels.

Appendix 3 contains an assessment of the potential for metals to leach from a roadbed using PG. The design of new roads affects the potential for exposures by creating a degree of isolation of the base layer from the environment. The PG in the proposed alternative use is placed above the water table and underneath the road's paved surface. Additionally, the roads are sloped to drain precipitation.[68] This limits water contact with the PG isolated within the base layer. Thus, for purposes of the Petition, leaching of PG to groundwater or surface water is likely not a complete exposure pathway of concern for roadbed use.

Lastly, groundwater protection is primarily governed by state law and is considered under federal and state highway guidance. The fact that materials utilized to construct roads can impact the environment has been reported by the NAS,[69] states,[70] and other federal agencies,[71] and applies to all road construction material, not just PG. States provide comprehensive guidance on roadway design.[72] Thus, regardless of the source of the road construction material, the federal,

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[67] *Id.* at 12.

[68] Appendix 3.

[69] The National Academies of Science, Assessing the Managing the Ecological Impacts of Paved Roads (2005) *available at* https://www.nap.edu/catalog/11535/assessing-and-managing-the-ecological-impacts-of-paved-roads.

[70] Idaho, Transportation Department Research Program, Impacts of Using Salt and Salt Brine for Roadway Deicing (2014), *available at* https://www.ctcandassociates.com/work-samples/saltimpacts.pdf.

[71] USDA, Reclaimed Materials and Their Application in Road Construction: A Condensed Guide for Road Managers (December 2013) *available at* https://www.fs.fed.us/t-d/pubs/pdfpubs/pdf12771807/pdf12771807dpi72.pdf. Northern European countries compile information on mitigation environmental impacts. Roadex Network, Environmental Considerations for Low Volume Roads, *available at* https://www.roadex.org/e-learning/lessons/environmental-considerations-for-low-volume-roads/preface-environmental/.

[72] Florida Department of Transportation, Manual of Uniform Minimum Standards for Design, Construction and Maintenance for Streets and Highways (Commonly known as the Florida Greenbook), Chapter 4 (2018) (draft)

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state, and local road building agencies will assess whether there is an impact from utilizing material A versus material B and decisions on how to mitigate any impacts is within the discretion of these agencies.

In summary, the presence of other substances that are not radionuclides in PG is unlikely to present an unacceptable worker exposure or adversely impact groundwater or surface water quality. The leaching pathway is likely not a complete pathway of concern for the PG use in road construction proposed in this Petition. Further, federal and state regulations require evaluation of and protection of groundwater prior to implementing road construction projects, regardless of what particular material is used, providing a further dimension of protection to the public.

I. Comparison of TFI Risk Assessment and Screening Evaluation with EPA's 1992 EPA Background Information Document (BID) Risk Assessment

Appendix 2 performed a very "high level" and preliminary overview of the main differences that we could readily identify between the dose and risk results provided in EPA's 1992 BID and those previously discussed in this report. The following is a list of comparisons:

- A 1:1 dilution of PG with soils (higher PG to soil than EPA's 1:2 PG to soil in 1992. Appendix 2, 1992 BID page 4-9).
- A road thickness of 0.25 m (the same as in 1992).
- The current risk assessment considers the same receptors as did EPA in 1992 as well as two additional receptors suggested by the EPA, namely, the truck driver transporting PG to the construction site and a utility worker who works some time in a trench cutting across a road constructed with PG.
- The EPA (at Table 4-16 for a road base of PG and sand) provided results for a variety of Ra-226 concentrations in PG, the highest of which is 26 pCi/g, comparable to our notional assumption of 27 pCi/g. This difference is not directly relevant since the risk is scalable from the notional assumed pCi/g level used.
- For the road construction worker, the EPA considered workers standing on the road base and unshielded, as was also assumed for the current risk assessment.
- The current risk assessment assumes a worker moves around over the road surface and is exposed at the average of the gamma fields at the center and edge of the road. While not fully clear, the EPA in 1992 may have assumed a worker was always in the center of the road which would largely account for the difference between gamma doses estimated in 1992 and now.

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available at https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/roadway/floridagreenbook/2018-florida-greenbook-web-draft.pdf?sfvrsn=b5d27e8b_4.

- The road user is assumed in both cases to drive on a road with PG base and a cover (in 1992 asphalt or cement) and in the present analysis, for purpose of illustration, concrete road surface was assumed. Only annual dose and risk are available from the 1992 risk assessment. The 1992 EPA risk assessment used a 0.6 shielding for the road user, but rather than determine the degree to which vehicles have changed in the amount of metal in the under carriage of cars, the current risk assessment takes no credit for shielding provided by the vehicle that would provide some level of shielding which is a conservative assumption and could reasonably be considered.

- The dose to the nearby resident is dominated by exposure to gamma radiation which decreases rapidly with increasing distance from the edge of the road. The 1992 risk assessment assumed the nearest resident would be at 100 meters (approximately 328 ft) from the edge of the road. The current assessment considers the RME exposure scenario to be a resident whose home is located a distance of 50 feet from the edge of the road (an urban resident whose home is at 20 feet from the edge of the road is also calculated to illustrated the change in exposure levels with distance).

- The 1992 BID mentions the presence of metals, but did not consider any substances other than radionculides in the 1992 risk assessment. The current risk assessment is relying upon the in-depth assessment performed for radionuclide in 1992. However, the current Petition includes a metals screening evaluation to justify the fact that a quantitative risk assessment is not warranted.

- The EPA BID risk assessments considered a reclaimer scenario with exposures from gamma radiation and radon, in which the surface is removed and a house is directly built upon PG, and a resident lives in the house for 70 years.

    - At EPA's request, this Risk Assessment calculated this reclaimer scenario, even though such a scenario is an extreme hypothetical case that is not a RME exposure. Both the 1992 and present calculation assume the surface is removed, but the current assessment takes into account the necessary construction site preparation and grading, which reduces the thickness and to a lesser degree, the concentration of residual road base construction activity that would be necessary to construct a house.

    - The 1992 BID does not indicate how the risk from radon was calculated (dose from radon was not reported in the 1992 BID).

    - The 1992 BID assumed 70-years residency and the current assessment assumed a 26-year residency (the upper 90th percentile). The 1992 BID appears to have used for the nearby resident scenarios values that are in the ballpark of 25 to 30 years. Thus, the 70-year residency for the reclaimer scenario in the 1992 BID appears to be inconsistent with the residency lengths used by EPA in other parts of the 1992 as well as current EPA guidance.

    - The current assessment also assumes a 6 ml poly layer which is standard as a vapor barrier in current home construction.

These comparisons demonstrate the upper bound nature of the risk assessment. Actual doses and risks are likely to be lower.

VI. RISK MANAGEMENT DECISION

A. Overview

The regulatory decision to approve a new use for PG is a risk management decision that is assigned to the Assistant Administrator for Air and Radiation. Risk management decisions involve weighing the results of a risk assessment with "the results of other technical analyses and nonscientific factors, to reach a decision about the need for and extent of risk reduction to be sought in particular circumstances and of the means for achieving and maintaining that reduction."[73]

This Petition and its Appendices provide the facts and science necessary to decide whether to approve this Petition. This subsection applies these facts and the science to EPA's risk management factors and articulates the reasons that TFI submits support approval.

B. The Risk Management Level of 3 in 10,000 is Consistent with Other NESHAP Goals

The EPA Office of Air and Radiation policy is that it will make a case-by-case decision concerning the acceptability of the risk from exposure to radionuclides.[74] However, the PG risk management limit of 3 in 10,000 is consistent with other typical EPA risk management decisions.

C. The Highest RME Risk Scenario for the Use of PG in Road Construction is Below the NESHAP Radionuclide Risk Management Goal of 3 in 10,000

This Petition demonstrates that the risks of using PG material in constructing roads meet the risk management goal for approved alternative uses of PG.

The risks from all exposure scenarios were calculated, but the highest RME risk is calculated for the road construction worker who is involved with paving the road with PG that is mixed with soil (i.e., a cancer risk of 0.5 in 10,000, lower than the PG alternative use risk management goal of 3 in 10,000). EPA has long concluded that 3 in 10,000 is the equivalent of the risk from the existing PG stacks, so this alternative does not present a meaningful difference in the risk from the existing stacks. The focus is on the road construction worker since the risks from all other exposure scenarios fall below 110 mrem during road construction use and are of lower risk, although the road worker's risk falls within EPA exposure limits as well.

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[73] Institute of Medicine, Environmental Decisions in the Face of Uncertainty, Box 2-1 (2013) *available at* https://www.ncbi.nlm.nih.gov/books/NBK200844/box/box_2_1/?report=objectonly (Uncertainty in Environmental Decisions).

[74] 1989 Rule, *supra* note 2, at 51,564.

The vast majority of road construction workers have much lower risks than those calculated in this Petition. Highway construction workers not directly working on the road are located further from the PG and have lower risks.

The risk calculation for the highest RME for a worker placing road base assumes that the PG emits 27 pCi/g exposure for five years. Based on the preliminary data on radiation levels from PG stacks, the average level of radioactivity from the PG material in each sampled stack is less than the nominal 27 pCi/g used in the risk assessment, thus, the risk from these sampled stacks is even further below the EPA risk management safe limit of 3 in 10,000 risk level. The calculated risk is scalable, i.e., if the radioactivity level in a stack is 13.5 pCi/g, the risk is one half of the risk calculated for the nominal radioactivity level of 27 pCi/g (i.e., the 12.5 pCi/g stack corresponds to a 0.275 in 10,000 risk level, significantly lower than the EPA PG risk limit of 3 in 10,000). On average, the RME exposure and the dose to risk conversion for road construction workers using PG are likely to overestimate risk.

Similarly, the highest RME to a resident living near a road (assuming the resident lives in a home located 50 feet or more from a road for 26 years) assuming the PG contains 27 pCi/g is approximately a 0.08 in 10,000 cancer risk, again, well below the PG reuse risk management goal of 3 in 10,000. Most residents living near roadways are located further than 50 feet from the edge of the road, and the RME exposure and dose to risk conversion are likely to overestimate risk.

The reclaimer scenario is not a RME since it is such a rare potential event, and should not be used in the risk management decision. Nonetheless, the risk assessment report calculated a risk using RME-type exposure input below the PG reuse risk management goal of 3 in 10,000.

D. Science Policy Assumptions and Uncertainties are Taken into Account in the Final Risk Management Decision

1. Overview

Each of the factors EPA considers in its risk management decision has sensitivities, variabilities, and uncertainties. EPA specifically considered uncertainties and other nonrisk factors in its 1989 and 1992 decisions on acceptable alternative uses of PG.[75]

A recent NAS report recommended incorporating uncertainty analysis, which was broadly defined to include sensitivities, variability, and various other uncertainties, into EPA decisions.[76] This NAS report recommends that "uncertainty analysis" be "designed on a case-by-case basis."[77] EPA considered uncertainties in previous risk calculations and decisions concerning

[75] EPA PG Workbook *supra* note 5, at 5.

[76] Institute of Medicine, Environmental Decisions in the Face of Uncertainty, 5 (2013) *available at* https://www.ncbi.nlm.nih.gov/books/NBK200840/ (Uncertainty in Environmental Decisionmaking).

[77] *Id.*

alternative uses of PG.[78] However, combining RME with the inherent uncertainties in the dose to risk conversion factors can yield risks that are overly conservative compared to actual risks.

Science policy influences both the exposure calculation and the cancer potency and noncancer risk factors that convert the exposure to risk. The EPA decision makers and the public need to understand how policy influences the risk calculation. Put simply, regulatory risk is not the same as actual harm. Unduly conservative risk calculations do not serve the public, since they divert limited resources to issues that present less risk. Science policy based on accumulations of conservative assumptions, including extra layers based on uncertainties, can distort risk estimates and undermine the value and credibility of risk management decisions.

2. **Measurement Uncertainty**

Each calculated risk depends upon how sensitive the calculation is to changes in the measurements and input values used in any risk assessment. Risk is assumed to be linearly proportional to dose and the length of exposure. For example, if the concentration of radionuclide in PG increases by 10%, the dose (and, therefore, the risk) increases by 10%. Similarly, if the length of exposure increases by 20%, the total dose increases by 20%.

3. **Variation by Location**

Some of the inputs to risk assessments naturally vary. For example, the average radioactivity level in PG stacks depends upon the source of the phosphate ore and other site specific factors. This risk assessment assumed average radioactivity levels of 27 pCi/g. However, the average level of radioactivity in some PG stacks may vary from less than 10 pCi/g to 35 pCi/g, and even at levels of 35 pCi/g, the Risk Assessment shows these doses are safe.[79] Again, dose is directly proportional to the radioactivity level.

4. **The Influence of Exposure Policies**

It is well settled that exposure is not sufficient to support regulation unless there is a significant risk.[80] Because empirical data are often not available, a 2013 National Academies of Science (NAS) report noted that EPA's risk assessment policies and practices rely heavily on default options or generic approaches.[81] These approaches can introduce high levels of uncertainty into risk assessments.

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[78] EPA PG Workbook, *supra* note 5, at 5.

[79] Based on the risk assessment, PG with radiation levels a couple of times greater than 27 pCi/g may still be utilized for road construction. In fact, an average radiation level of 148 pCi/g corresponds to EPA's risk management goal of 3 in 10,000.

[80] "When the administrative record reveals only scant or minimal risk of material health impairment, responsible administration calls for avoidance of extravagant, comprehensive regulation. Perfect safety is a chimera; regulation must not strangle human activity in the search for the impossible." *Industrial Union Dep't. v. API*, 448 U.S. 607, 642 (1980). *See NRDC v. EPA*, 1987, *supra* note 41, at 1164-65.

[81] Uncertainty in Environmental Decisions, *supra* note 76, at 58, *available at* https://www.nap.edu/read/12568/chapter/4#58. *Also see* National Research Council, Science and Judgment in Risk Assessment, 65 (1994), *available at* http://www.nap.edu/openbook.php?record_id=2125&page=65 and the General

As noted above, the "intent of the RME is to estimate a conservative exposure case (i.e., well above the average case) that is still within the range of possible exposures."[82] A NAS Committee reviewing EPA's regulation of technologically enhanced naturally occurring radioactive material (TENORM) recommended that EPA "should use exposure and dose risk assessments that are 'reasonably realistic'" in developing standards for exposure to the various types of low level naturally occurring radiation.[83] The Committee defined "reasonably realistic" as "not....intended to greatly overestimate or underestimate actual effects for the exposure situation of concern" and EPA agreed with the Committee's recommendations.[84] Thus, by definition, RME exposures should be intentionally set at levels that are at the high end, but not an extreme worst case.

The use of defaults has been criticized by independent commentators for: (a) "lack of an adequate scientific basis;" (b) the fact that default "can mask the uncertainty;" (c) observations that defaults can be "overly conservative;" (d) the fact that cumulative impact of uncertainties is not well defined; and (e) concerns "whether there is any basis for believing that the upper-bound estimate for one substance has the same relation to the 'true' risk as it does for another substance."[85]

5. Risk Factor Policies and Uncertainties

EPA has long utilized (and courts have long upheld) the principle that a 1 in 10,000 risk level is "safe." As a unanimous *en banc* ruling of the Court of Appeals for the District of Columbia Circuit candidly noted, the basis for claiming harm from exposure to chemicals at extremely low environmental levels is more a function of "the rules of arithmetic rather than because of any knowledge" and there was "no particular reason to think that the actual line of the incidence of harm is represented" by the assumption selected by EPA.[86] This acknowledgment is also apt for the risks from radionuclides.

Accounting Office, Use of Precautionary Assumptions in Health Risk Assessments and Benefits Estimates, GAO-01-55, 7 (October 2000).

[82] Risk Assessment Guidance for Superfund, *supra* note 35, at 7-2.

[83] EPA Report to Congress Re: TENORM, *supra* note 37, at 15.

[84] *Id.* at 15 of 22, citing the NAS Report at p. 245. "If high-end values are chosen for every exposure factor, then the resulting exposure estimate may no longer be consistent with the RME and may exceed the realm of possibility altogether." EPA, Human Health Evaluation Manual, Supplemental Guidance: Update of Standard Default Exposure Factors, OSWER Directive 9200.1-120 (Feb. 6, 2014) *available at* https://www.epa.gov/sites/production/files/2015-11/documents/oswer_directive_9200.1-120_exposurefactors_corrected2.pdf.

[85] Uncertainty in Environmental Decisions, *supra* note 76, at 58, *available at* https://www.nap.edu/read/12568/chapter/4#58. The RME and other factors utilized in the risk assessment are documented in the literature (*see* RESRAD documentation, EPA guidance or as justified in the various Appendices to this Petition).

[86] *NRDC v. EPA*, 1987, *supra* note 41, at 1165.

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The 2013 NAS noted that:

> EPA originally selected the linear, no-threshold default as a "conservative" or "health-protective" policy choice because it assumes that there is no dose below which risks are not increased. It is likely to generate the highest, or upper-bound, risk estimate consistent with the data; the actual risk almost certainly will not exceed the upper bound and will likely fall below it.[87]

Use of the ICRP value (the value proposed by the international institution whose purpose is to provide such advice) is supported by several factors:

First, ICRP is an expert advisory body that offers its recommendations to regulatory and advisory agencies, mainly by providing guidance on the fundamental principles on which appropriate radiological protection is based. The 2007 recommendation was produced "after eight years of discussions, involving scientists, regulators, and users all around the world."[88]

Second, the Petition's use of the ICRP dose to risk conversion factor is consistent with EPA's radiation risk assessment factors and procedures. For example, the EPA 2011 radiation guidance[89] provides cancer risk factors for uniform whole-body exposures of low-dose gamma radiation to the entire population, essentially the same dose to risk conversion range derived by the ICRP.

Similarly, as noted above, the organization chartered by the U.S. Congress in 1964 to, among other things, "develop … recommendations about …protection against radiation" (i.e., the United States National Council on Radiation Protection and Measurements (NCRP)) uses the same dose to risk conversion factor as the 2007 ICRP.[90]

Third, the international scientific and regulatory communities have widely adopted the ICRP recommendations.[91]

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[87] Uncertainty in Environmental Decisions, *supra* note 76, at 58, *available at* https://www.nap.edu/read/12568/chapter/4#58.

[88] The 2007 Recommendations of the International Commission on Radiological Protection, *supra* note 49, at 3.

[89] EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population, *supra* note 53.

[90] Management of Exposure to Ionizing Radiation: Radiation Protection Guidance for the United States, *supra* note 54, at 42.

[91] *See* Radiation Protection and Management of NORM Residues in the Phosphate industry, *supra* note 24, at 165. The IAEA was founded to "establish or adopt … standard of safety for protection of health and minimization of danger to life and property" and while "[r]egulating safety is a national responsibility . . . many have decided to adopt the IAEA's standards for use in their national regulations" (including Sweden, Denmark, the Netherlands, the UK, Japan, Canada, Belgium, Japan, and the EU). IAEA, Governmental, Legal and Regulatory Framework for Safety, 7 (2018) *available at* https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1798_web.pdf.

See Council Directive 2013/59/Euratom, *supra* note 56.

See UNSCEAR, Report of the United Scientific Committee on the Effects of Atomic Radiation, 8 and n. 17 (2010) (includes Scientific Report: summary of low-dose radiation effects on health, 2011) (UNSCEAR Report).

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Fourth, the International Atomic Energy Agency (an organization in which the U.S. is a member and helped establish) and the European Union (as well as each of its member countries) utilized a 1 millisievert (1 mSv) per year acceptable level of radiation exposure, which has been widely adopted by the international community, such as the IAEA and EU regulations. This corresponds to a 26-year total dose of 26 mSv (i.e., 2,600 mrem).

The ICRP approach is more stringent than the large, and growing, body of scientific literature that radiation risks have a threshold. Also, in 2015, a U.S. Nuclear Regulatory Commission (NRC) Advisory Committee acknowledged that:

> There is a large, and growing, body of scientific literature as well as mechanistic considerations which suggest that 1) the LNT model may overstate the carcinogenic risk of radiation at diagnostic medical, occupational, and environmental doses and 2) such low doses may, in fact, exert a hormetic (i.e., a beneficial or protective) effect.[92]

The United Nations Scientific Committee on the Effects of Atomic Radiation notes that below doses of 100 to 200 mGy (roughly equivalent to 10,000 to 20,000 mrem), "[e]pidemiological studies alone are unlikely to be able to identify significant elevations in risk."[93]

Because, as a matter of policy, neither EPA nor the Nuclear Regulatory Commission has changed its "no threshold" default assumptions, this Petition does not seek to go beyond the widely accepted ICRP value. In reality, the actual risk may be lower.

E. Comparison of Radioactivity Levels from Use of PG and Naturally Occurring Background

Each exposure scenario we assessed results in a radiation dose well below the annual natural background level. The annual background level of naturally occurring radiation is 310 mrem.[94] For a 26 year period, the cumulative dose is 8,060 (310 mrem times 26), thus the total dose for a nearby resident (16 mrem) given this PG use is 0.2% of the cumulative natural background dose levels (16 divided by 8,060). Background levels of radiation are often considered in governmental decisions. For example, EPA's PG Workbook compares the risk from use of PG to background levels of radiation.[95] When the calculated risk for receptors in a risk assessment is lower than background, it is a relevant factor in the risk management decision.

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[92] Nuclear Regulatory Commission, Advisory Committee on the Medical Uses of Isotopes (ACMUI), Report on the Hormesis/Linear No-Threshold Petitions, 1 (October 14, 2015), *available at* https://www.nrc.gov/docs/ML1528/ML15287A494.pdf.

[93] UNSCEAR Report, *supra* note 91, at 8.

[94] Appendix 2.

[95] EPA PG Workbook, *supra* note 5, at 13 ("To put this number in perspective and allow you to see how little increase in risk is permitted, the risk in the United States of developing a fatal cancer (from all causes) is about one in four").

F. EPA Policy Supports Recycling of Wastes and Waste Residuals

EPA's 1989[96] and 1992[97] risk management decisions concerning alternative uses of PG took into account the Agency's overarching policy of supporting recycling. Since 1992, EPA has increased its emphasis on adopting sustainability policies.

EPA has prioritized policies to encourage recycling of byproducts and other materials.[98] Similarly, the U.S. Department of Agriculture also has guidance on using reclaimed materials in road construction.[99] Such recycling decreases raw material costs for companies and government entities that use the PG material, increases beneficial land use, reduces long-term maintenance costs, and avoids with respect to coal ash, site-specific potential environmental risks from long term storage of PG. For example, EPA states that:

> Beneficial use is the recycling or reuse of coal ash in lieu of disposal. For example, coal ash is an important ingredient in the manufacture of concrete and wallboard, and EPA supports the responsible use of coal ash in this manner. This final rule supports the responsible recycling of coal ash by distinguishing beneficial use from disposal.[100]

EPA recently concluded that:

> [E]nvironmental releases of COPCs from CCR fly ash concrete and FGD gypsum wallboard during use by the consumer are comparable to or lower than those from analogous non-CCR products, or are at or below relevant regulatory and health-based benchmarks for human and ecological receptors. Thus, EPA supports the continued beneficial use of coal fly ash in concrete and FGD gypsum in wallboard. Furthermore, the Agency believes that these beneficial uses provide significant environmental and economic benefits, and opportunities to advance Sustainable Materials Management (SMM).[101]

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[96] 1989 Rule, *supra* note 2.

[97] 1992 Rule, *supra* note 16, at 23,306.

[98] "Sustainable Materials Management (SMM) refers to the use and reuse of materials in the most productive and sustainable way across their entire life cycle. On a broader scale, SMM looks at social, environmental and economic factors to get a more holistic view of the entire system. The benefits of maximizing this connection include conserving resources, reducing waste, slowing climate change, and minimizing the environmental impacts of the materials we use." EPA, Advancing Sustainable Materials Management: 2016 Recycling Economic Information (REI) Report, 2 (2016), *available at* https://www.epa.gov/sites/production/files/2017-05/documents/final_2016_rei_report.pdf.

[99] Reclaimed Materials and Their Applications in Road Construction, *supra* note 71.

[100] EPA, Frequent Questions about Beneficial Use of Coal Combustion residuals (CCR) (last updated March 26, 2019) *available at* https://www.epa.gov/coalash/frequent-questions-about-beneficial-use-coal-ash.

[101] EPA, Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard, 5-25 (2014), *available at* https://www.epa.gov/sites/production/files/2014-12/documents/ccr_bu_eval.pdf (Coal Cumbustion Residual Beneficial Use Evaluation).

The use of CCR for beneficial use in road construction is analogous to and supports the Office of Air and Radiation's approval of the use of PG in road construction. More generally, approval of the use of PG in road construction is consistent with EPA's policy of encouraging recycling.

G. Naturally Occurring Background Radioactivity and Metals are Present Widely in the Environment, Including Existing Road Construction Materials

Many consumer products contain radioactive components (smoke detectors, clocks and watches, older camera lenses, older gas lantern mantles, older televisions and computer monitors, sun lamps and tanning salons, ceramic materials such as tiles and pottery, glassware, and some EXIT signs, among other products).[102] Most consumer products contain metals. Similarly, "[r]adioactive materials (including uranium, thorium, and radium) exist naturally in soil and rock."[103] Essentially all air contains radon and many types of soil and natural rock emit radiation.[104] In addition, virtually all road construction materials contain radioactivity and metals.

Coal ash, fly ash, bottom ash, natural gypsum, and other common construction materials contain radioactive material (see Table below).[105]

A 2014 evaluation of coal ash beneficial uses concluded that:

> All of the existing evaluations identified concluded that radiation exposures from fly ash concrete are not a major source of concern. Several of these existing evaluations compared fly ash concrete to analogous products and found that the potential exposures do not represent an appreciable addition to the background radiation that the general public is subjected to on an annual basis. Naturally occurring radionuclides are present throughout the environment in food, air, water, soil, consumer products, and even the human body. All natural resources used in building construction (e.g., cement blocks, bricks, granite, soil, rocks) contain some trace level of naturally occurring radionuclides. For example, the USGS concluded that "the radioactivity of typical fly ash is not significantly different from that of more conventional concrete additives or other building materials such as granite and red brick." The NCRP concluded that exposures from living in concrete buildings containing fly ash are "similar to calculations made for individuals living in a brick and masonry home. Consequently, it is assumed that the use of [coal ash] in building materials has not substantially increased the average dose to an individual in the population residing in a building constructed with brick or masonry materials."[106]

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[102] EPA, What kinds of consumer products contain radioactive materials (last updated on September 19, 2019) *available at* https://www.epa.gov/radiation/what-kinds-consumer-products-contain-radioactive-materials.

[103] U.S. Nuclear Regulatory Agency, Natural Background Sources (last updated October 2, 2017) *available at* https://www.nrc.gov/about-nrc/radiation/around-us/sources/nat-bg-sources.html#terr.

[104] *Id.*

[105] EPA Report to Congress Re: TENORM, *supra* note 37, at Appendix A.

[106] Coal Combustion Residual Beneficial Use Evaluation, *supra* note 101, at 1-7.

The United Kingdom Health Protection Agency "concluded that exposures to '…members of the public from the use of [fly ash] in building materials is negligible.'"[107]

Thus, the appropriate risk management consideration is not whether PG has a low level of radioactivity or metals, but whether the risk is below the EPA PG risk management goal of 3 in 10,000.

[107] *Id.*

Table copied (without footnotes) from "Appendix A – Table 1, TENORM Materials and References."

As a comparison to background levels, radium 226 concentrations in soils of the U.S. are shown at the top of the table.

TENORM Material	Range of Radioactivity Concentrations, Radium 226		
	Low	Average	High
Soils of the United States [1]	0.2	1.1	4.2
Uranium Mining Overburden [2]	3	3.0	low hundreds
Uranium In-Situ Leach Evaporation Pond Solids [3]	300	–	3,000
Phosphate Ore (Florida) [4]	7	17.3-39.5	6.2-53.5
Phosphogypsum [5]		11.7-24.5	36.7
Phosphate Fertilizer [6]		5.7	21
Coal Ash [7]-Bottom Ash	1.6	3.5-4.6	7.7
Fly Ash	2	5.8	9.7
Petroleum (oil and gas)	0.1 pCi/l	–	9000 pCi/l
Produced Water [8]	<0.25 pCi/g	<200 pCi/g	>100,000 pCi/g
Pipe/Tank Scale [9]			
Water Treatment Sludge [10]	1.3 pCi/l	11 pCi/l	11,686 pCi/l
Treatment Plant Filters [11]	–	40,000 pCi/g	–
Rare Earths [12]	5.7	–	3,244
Monazite			
Xenotime			
Bastnasite			
Titanium Ores [13]	3.9	8.0	24.5
Rutile	–	19.7	–
Ilmenite	–	5.7	–
Wastes	–	12	–
Zircon [14]	–	68	–
Wastes	87	–	1300
Aluminum [15] (Bauxite) Ores	4.4	–	7.4
Product	–	0.23	–
Wastes	–	3.9-5.6	–
Copper Wastes [16]	0.7	12	82.6
Geothermal Energy Waste Scales [17]	10	132	254

H. Use of PG For Roadway Construction Provides a Net Economic Benefit and is Consistent with the Administration's Regulatory Reform Policies

A detailed report explaining the various economic benefits to be expected from approval of PG use in road construction will be submitted shortly in support of this Petition.

The Petition is consistent with Presidential Executive Orders that encourage: (a) reducing unnecessarily burdensome and costly regulation;[108] (b) maximizing the use of goods, products and materials produced in the U.S.;[109] and (c) encouraging innovative strategies and trade policies.[110]

I. Other Benefits to Eliminating PG Stacks

Construction and maintenance of PG stacks are large engineering projects. There are environmental and actuarial risks presented by any such construction project. The approval of PG for use in road construction will reduce future potential risk by limiting the size of existing and potentially eliminating the need for new PG stacks.

[108] Presidential Executive Order on Reducing Regulation and Controlling Regulatory Costs, Executive Order 13771 (Jan. 31, 2017).

[109] Presidential Executive Order on Buy American and Hire American, Executive Order 13788 (April 18, 2017).

[110] Presidential Executive Order on Establishment of Office of Trade and Manufacturing Policy, Executive Order 13797 (April 29, 2017).

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SIGNATURE PAGE

I, Andrew (Andy) T. O'Hare, CAE, am Vice President of Public Policy for The Fertilizer Institute (the national trade association for fertilizer companies, including the companies that own and/or operate phosphogypsum stacks). I coordinated the preparation of this Petition and am signing on behalf of all of the TFI members who own or operate PG stacks.

Andrew T. O'Hare

Andrew (Andy) T. O'Hare

Vice President of Public Policy

The Fertilizer Institute

The Fertilizer Institute

Chart Legend:

ACTIVITY TYPE	ACTIVITY	STAFF	PLAN START	PLAN END DATE	PLAN DURATION	ACTUAL START	ACTUAL END	ACTUAL DURATION
Contractor Review Process	Discussion with SC&A task manager to review scope of WA	Walsh	10/28/2019	11/8/2019	11			0
Contractor Review Process	Initiate biweekly meetings with contract staff (alternate with EPA internal meetings)	Walsh	11/1/2019	11/8/2019	7			0
Contractor Review Process	First draft of report with complete review of model assumptions and	SC&A	11/1/2019	12/6/2019	35			0
Contractor Review Process	EPA comments back to SC&A	EPA Team	12/6/2019	12/16/2019	10			0
Contractor Review Process	Second draft of report with model runs/calculations completed. Technical determination of whether the risk determination is supported	SC&A	12/16/2019	1/17/2020	32			0
Contractor Review Process	EPA comments back to SC&A	EPA Team	1/17/2020	1/27/2020	10			0
Contractor Review Process	Final report due	SC&A	1/27/2020	2/14/2020	18			0
EPA Internal Technical/Policy Review	Team kickoff meeting to describe roles and milestones	EPA Team	10/30/2019	11/8/2019	9			0
EPA Internal Technical/Policy Review	G: drive populated	Walsh	10/28/2019	11/1/2019	4			0

ACTIVITY TYPE	ACTIVITY	STAFF	PLAN START	PLAN END DATE	PLAN DURATION	ACTUAL START	ACTUAL END	ACTUAL DURATION
EPA Internal Technical/Policy Review	Complete first read of TFI application and background documents	EPA Team	10/30/2019	11/8/2019	9			0
EPA Internal Technical/Policy Review	Review internal issue list, begin tracking resolutions biweekly	EPA Team	11/4/2019	11/14/2019	10			0
EPA Internal Technical/Policy Review	Initial reports on internal technical and policy assignments (reports in outline	EPA Team	11/18/2019	11/26/2019	8			0
EPA Internal Technical/Policy Review	EPA team reviews SC&A first draft; crosswalk with internal questions and	EPA Team	12/9/2019	12/13/2019	4			0
EPA Internal Technical/Policy Review	EPA comments back to SC&A	EPA Team	12/9/2019	12/16/2019	7			0
EPA Internal Technical/Policy Review	Determine content and format of EPA internal report	EPA Team	12/16/2019	12/20/2019	4			0
EPA Internal Technical/Policy Review	Internal report sections due	EPA Team	1/13/2020	1/17/2020	4			0
EPA Internal Technical/Policy Review	EPA internal review of contractor draft #2	EPA Team	12/20/2019	1/24/2020	35			0
EPA Administrative Process	Send application to Charles (FYI)	Walsh	10/22/2019	10/22/2019	0	10/22/2019	10/22/2019	0
EPA Administrative Process	CWMR management reviews schedule	Walsh	10/25/2019	10/25/2019	0	10/25/2019	10/25/2019	0
EPA Administrative Process	Pre-brief for Lee w/ ORIA briefing materials. Will include status of technical work and policy options	Walsh	10/28/2019	11/8/2019	11			0
EPA Administrative Process	Lee informal updates Jon E. Discuss RPD's preferred strategy/recommendation to the AA?	RPD Management	10/28/2019	11/8/2019	11			0

ED_005285_00000285-00002

ACTIVITY TYPE	ACTIVITY	STAFF	PLAN START	PLAN END DATE	PLAN DURATION	ACTUAL START	ACTUAL END	ACTUAL DURATION
EPA Administrative Process	Briefing for Jon E. on application	Walsh	11/12/2019	11/22/2019	10			0
EPA Administrative Process	Present updated policy options to RPD management and OGC/ARLO	Walsh	11/25/2019	12/6/2019	11			0
EPA Administrative Process	Develop proposed approval strategy and conditions w/OGC/ARLO	Walsh/OGC	12/30/2019	1/17/2020	18			0
EPA Administrative Process	Schedule meeting (for late Jan) with TFI to resolve any remaining technical	Walsh	1/6/2020	1/10/2020				0
EPA Administrative Process	Brief RPD on status of technical review	Walsh	1/6/2020	1/10/2020	4			0
EPA Administrative Process	(Optional) Informal briefing for Jon E. on status of technical review and policy options	Walsh	1/8/2020	1/17/2020	9			0
EPA Administrative Process	Report contractor's technical risk determination to RPD management		1/21/2020	1/24/2020	3			0
EPA Administrative Process	Notify OLEM		1/21/2020	1/24/2020	3			0
EPA Administrative Process	Meet with TFI to resolve any remaining technical questions, and propose		1/22/2020	1/31/2020	9			0
EPA Administrative Process	Propose response strategy to OGC/ARLO		1/27/2020	1/31/2020	4			0
EPA Administrative Process	OGC concurrence		1/31/2020	2/14/2020	14			0
EPA Administrative Process	Draft & complete comms plan		2/14/2020	3/1/2020	16			0
EPA Administrative Process	Brief Anne Idsal		2/24/2020	2/28/2020	4			0
EPA Administrative Process	Federal Register notice submitted		3/1/2020	3/9/2020	8			0

ED_005285_00000285-00003

ACTIVITY TYPE	ACTIVITY	STAFF	PLAN START	PLAN END DATE	PLAN DURATION	ACTUAL START	ACTUAL END	ACTUAL DURATION
EPA Administrative Process	Federal Register notice published		3/16/2020	3/27/2020	11			0
EPA Administrative Process	Federal Register comment period closes		3/27/2020	4/26/2020	30			0
EPA Administrative Process	Federal Register comment period 15 day extension (likely)		4/26/2020	5/11/2020	15			0
EPA Administrative Process	Comment review		4/26/2020	6/11/2020	46			0

ED_005285_00000285-00004

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 8/13/2020 8:26:23 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]

Ex. 5 Deliberative Process (DP)

Appointment

From: Holden, Patricia [Holden.Patricia@epa.gov]
Sent: 11/18/2020 2:38:37 PM
To: OAR-ORIA-RPD [OARORIARPD@epa.gov]; Yale, Kenneth [yale.kenneth@epa.gov]; Xinyue Tong [dennistong@utexas.edu]; Major, Jonathan [Major.Jonathan@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]
CC: Holden, Patricia [Holden.Patricia@epa.gov]; Tong, Xinyue [Tong.Xinyue@epa.gov]; Snead, Kathryn [Snead.Kathryn@epa.gov]; Hellberg, Dennis [Hellberg.Dennis@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Littleton, Brian [Littleton.Brian@epa.gov]; Hallam, Christopher [Hallam.Christopher@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]; Rosencrantz, Ingrid [Rosencrantz.Ingrid@epa.gov]; DeCair, Sara [DeCair.Sara@epa.gov]; Nelson, Neal [Nelson.Neal@epa.gov]; Anoma, Valentine [Anoma.Valentine@epa.gov]; Shogren, Angela [Shogren.Angela@epa.gov]; Wang, Ellen [wang.ellen@epa.gov]; Ellis, Jerry [Ellis.Jerry@epa.gov]; Arrigoni, Holly [Arrigoni.Holly@epa.gov]; White, Rick [White.Rick@epa.gov]; Clark, Ray [Clark.Ray@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Feltcorn, Ed [Feltcorn.Ed@epa.gov]; Whitaker, Theresa [Whitaker.Theresa@epa.gov]; Chen, Gary [chen.gary@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Matakas, Lauren [matakas.lauren@epa.gov]; Thornton, Marisa [Thornton.Marisa@epa.gov]; Boyd, Mike [Boyd.Mike@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Miller, Beth [Miller.Beth@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Preston, Julian [Preston.Julian@epa.gov]; Prioleau, Wagnus [prioleau.wagnus@epa.gov]; Pawel, David [Pawel.David@epa.gov]

Subject: RPD Division Meeting
Attachments: Divison Meeting Presentation_November2020 _CWMR_TFI_Walsh2_11 18 2020.pptx
Location: Microsoft Teams Meeting

Start: 11/18/2020 4:00:00 PM
End: 11/18/2020 5:00:00 PM
Show Time As: Tentative

Recurrence: Weekly
every 4 week(s) on Wednesday from 11:00 AM to 12:00 PM

Join Microsoft Teams Meeting

Ex. 6 Personal Privacy (PP) nited States, Washington DC (Toll)

Conference ID: Ex. 6 Personal Privacy (PP)

Local numbers | Reset PIN | Learn more about Teams | Meeting options

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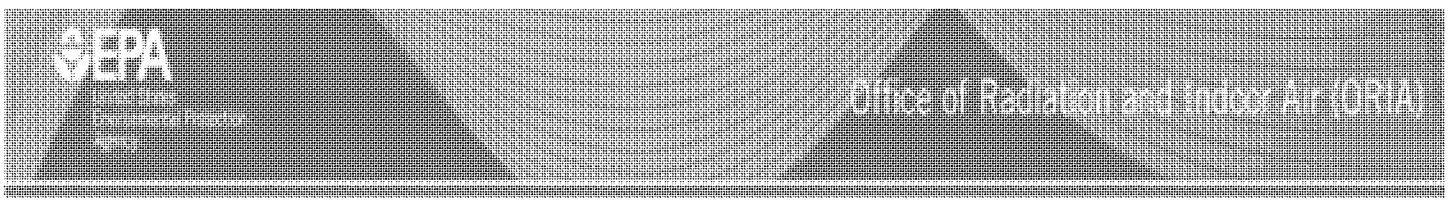
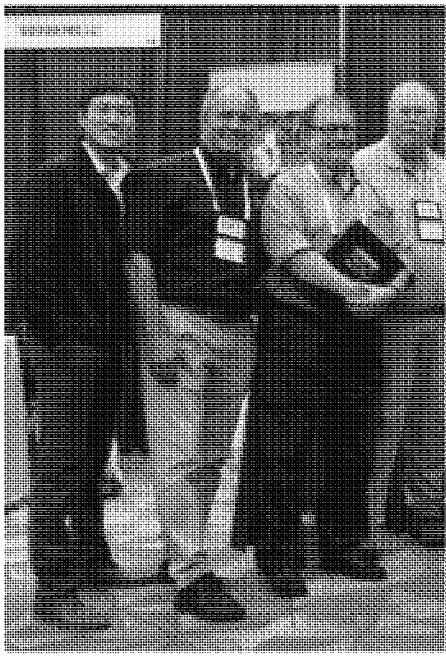
Message

From: Marbury, Candice [Marbury.Candice@epa.gov]
Sent: 9/27/2019 12:43:24 PM
To: White, Rick [White.Rick@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Jackson, Scott [Jackson.Scott@epa.gov]; Esher, Diana [Esher.Diana@epa.gov]; Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Stewart, Gretchen [Stewart.Gretchen@epa.gov]; Millett, John [Millett.John@epa.gov]; Shaw, Betsy [Shaw.Betsy@epa.gov]; Febbo, Carol [febbo.carol@epa.gov]; Zhen, Davis [Zhen.Davis@epa.gov]; Perry, Stuart [Perry.Stuart@epa.gov]; Snowbarger, Robert [Snowbarger.Robert@epa.gov]; Jencius, Michele [jencius.michele@epa.gov]; Lewis, Josh [Lewis.Josh@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]; Rowson, David [Rowson.David@epa.gov]; Smith, Alisa [Smith.Alisa@epa.gov]; Griggs, John [Griggs.John@epa.gov]; Clark, Mike S. [Clark.Michael@epa.gov]; Stafford, Andrea [Stafford.Andrea@epa.gov]; Wilds, Edward [Wilds.Edward@epa.gov]; Idsal, Anne [idsal.anne@epa.gov]
CC: Murphy, Stacy [Murphy.Stacy@epa.gov]; Szabo, Stephen [Szabo.Stephen@epa.gov]; Moyer, Michelle [moyer.michelle@epa.gov]; LeSane, Heidi [Lesane.Heidi@epa.gov]; Berry, Mark [Berry.Mark@epa.gov]; Mollsen, Helen [mollsen.helen@epa.gov]; Paguia, Monica [paguia.monica@epa.gov]; Mitchell, Ken [Mitchell.Ken@epa.gov]; Banister, Beverly [Banister.Beverly@epa.gov]; Arnold, David [arnold.david@epa.gov]; McTigue, Erin [McTigue.Erin@epa.gov]; Eagles, Tom [Eagles.Tom@epa.gov]; Childers, Pat [Childers.Pat@epa.gov]; Melanson, Kate [Melanson.Kate@epa.gov]; Jablonowski, Eugene [jablonowski.eugene@epa.gov]; Burke, Dan [Burke.Dan@epa.gov]; Benoit, Eugene [benoit.eugene@epa.gov]; Julien, Rhona [julien.rhona@epa.gov]; Mehta-Sampath, Ameesha [Mehta-Sampath.Ameesha@epa.gov]; Schulingkamp, Cristina [schulingkamp.cristina@epa.gov]; Bolden, Janice [Bolden.Janice@epa.gov]; Blakely, Lashon [Blakely.Lashon@epa.gov]; Batka, Sheila [Batka.Sheila@epa.gov]; Marrero, Jeanette [Marrero.Jeanette@epa.gov]; Aquino, Marcos [Aquino.Marcos@epa.gov]; Barry, Michael [Barry.Michael@epa.gov]; Brozowski, George [brozowski.george@epa.gov]; Generette, Lloyd [Generette.Lloyd@epa.gov]; Honnellio, Anthony [Honnellio.Anthony@epa.gov]; Hooper, Charles A. [Hooper.CharlesA@epa.gov]; Knutson, Lingard [Knutson.Lingard@epa.gov]; Povetko, Oleg [Povetko.Oleg@epa.gov]; Richards, Jon M. [Richards.Jon@epa.gov]; Mahler, Tom [mahler.tom@epa.gov]; Wagner, Christine [Wagner.Christine@epa.gov]; Waldon, MARGARET [Waldon.Margaret@epa.gov]; Pathak, Priyanka [Pathak.Priyanka@epa.gov]; Hulting, Melissa [hulting.melissa@epa.gov]; Fuoco, Marta [fuoco.marta@epa.gov]; Paguia, Monica [paguia.monica@epa.gov]; Worley, Gregg [Worley.Gregg@epa.gov]; Davis, Amber [Davis.Amber@epa.gov]; Cooper, Artra [Cooper.Artra@epa.gov]; Woodruff, Kevin [Woodruff.KevinL@epa.gov]; Jay, Michael [Jay.Michael@epa.gov]; Algoe-Eakin, Amy [Algoe-Eakin.Amy@epa.gov]; Cooper, Artra [Cooper.Artra@epa.gov]; Payan, Melissa [Payan.Melissa@epa.gov]; Iglesias, Ariel [Iglesias.Ariel@epa.gov]; Siegel, Kathryn [siegel.kathryn@epa.gov]; Perez, Idalia [Perez.Idalia@epa.gov]; Azzam, Nidal [Azzam.Nidal@epa.gov]; McAuley, Jim [mcauley.jim@epa.gov]; MUSANTE, JASON [Musante.Jason@epa.gov]; Godfrey, Althea [godfrey.althea@epa.gov]; Meindl, Andrew [meindl.andrew@epa.gov]; Weiss, Benjamin [weiss.benjamin@epa.gov]; Milhollin, Chandler [Milhollin.Chandler@epa.gov]; Freed, Rachel [freed.rachel@epa.gov]; Stoliarova, Janise [Stoliarova.Janise@epa.gov]; Bird, Patrick [Bird.Patrick@epa.gov]; Payan, Melissa [Payan.Melissa@epa.gov]; Walters, Margaret [Walters.Margaret@epa.gov]
Subject: ORIA Weekly - The Week Ending September 27, 2019
Attachments: ORIA Weekly September 27 2019.docx

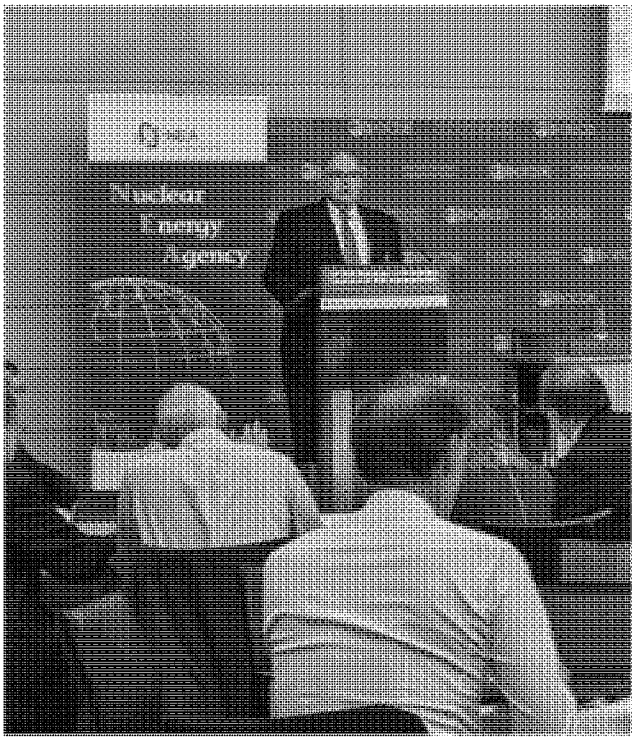


ORIA Weekly – September 27, 2019

RECENT EVENTS



RPD and Regional Staff along with ORIA Director Attended Naturally Occurring Radioactive Material (NORM) IX Symposium – See9/20/19 ORIA Weekly for more details



RPD's Boyd and Wieder Participated in the Nuclear Energy Agency (NEA) Workshop on Stakeholder Involvement: Risk Communication – See 9/20/19 ORIA Weekly for more details.

- **RPD's Nesky Participated in U.S.-Japan Bilateral Emergency Management Working Group** – See 9/20/19 ORIA Weekly for more details.
- **IED Convened the Asthma Community of Practice Meeting** – See 9/20/19 ORIA Weekly for more details.

- **IED's Mitchell Participated in the President's Task Force Meeting on Environmental Health Risks and Safety Risks to Children –** See 9/20/19 ORIA Weekly for more details.

RadNet Report for the Week of September 16, 2019

Overall monitor operational percentage was 90.3%. This is above the operational goal of 80%.

UPCOMING EVENTS (As of September 27)

Indoor Air Quality

- **IED's Hurst and Johnson to Present Indoor airPLUS Leader Awards During National Sustainable Building Summit:** On October 1-3, in Denver, CO, IED's Nick Hurst and Aaron Johnson will participate in the 2019 Energy and Environmental Building Alliance (EEBA)

Summit. EEBA is among the oldest and most respected residential building education organizations in the country. Approximately 400 industry homebuilders, home energy raters, and product manufacturers will attend the summit to share best practices for healthy, energy-efficient design and construction techniques. Indoor airPLUS is a sponsor for the summit's education sessions. Nick will deliver a presentation on radon-resistant construction, moderate a panel discussion on indoor air quality, and serve as a Technical Advisor in the EEBA Board Meeting. Nick and Aaron will also present the 2019 *Indoor airPLUS Leader Awards* to ten winning builder and rater partners and highlight their participation and achievements over the last year. At the end of the award ceremony, the Indoor airPLUS "Leaders of the Year" in the builder and rater category will be publicly announced and recognized.

- **IED's Schools Team to Host 3-part Webinar Series on IAQ and Healthy Green Cleaning in Schools:** On October 3, during Children's Health Month, the IED's Schools Team will rebroadcast the first of three popular IAQ and Healthy Green Cleaning in Schools webinars entitled, "*Clean Bill of Health; How Effective Cleaning and Maintenance Can Improve Health Outcomes in Your School*". The webinar will teach participants how to establish cleaning and maintenance training programs to increase efficiency and protect the health of the cleaning staff. School staff will learn how to train and prepare staff to implement a preventive maintenance plan to reduce costs and improve health by using effective cleaning practices. These webinars are part of the IAQ in Schools Master Class and IAQ Knowledge to Action Professional Series.

- **Tribal Air Monitoring Support (TAMS):** The week of September 30, in Washington, DC, NCRFO's Farshid Farsi is attending EPA's Tribal Air Coordinator's (TAC) Meeting. This meeting is an open forum for the regional offices to share insights regarding their work with their tribal professional constituents. The TAMS Center will provide a presentation regarding TAMS technical services available to the tribes and discuss opportunities to improve communications with the TACS in providing those services to the tribes.

Radiation Protection and Emergency Response

- **RPD's DeCair to Attend Nuclear Energy Agency (NEA) Expert Group on Recovery Management:** On October 1-2, in Bristol, UK, RPD's Sara DeCair will co-facilitate a two day meeting of an Organization for Economic Co-operation and Development, NEA-sponsored working group on best managing the long term recovery after a radiological accident or attack. A group of experts from numerous countries around the world will share real-world experiences, best practices and pitfalls to avoid and pull together a set of recommendations aimed at improving future disaster recoveries. Recent experience with garnering more public trust and ongoing radioactive waste management efforts in Japan will be a key feature of the discussion. The end result of this effort is anticipated to be a summary of best practices and recommendations published by the NEA.

- **New Facility to be Shown at Continuity of Operations (COOP) Open House:** On October 3 and 9, in Mt. Weather, Virginia, OAR Emergency Relocations Group personnel will attend open house information sessions at the new EPA COOP facility. COOP Personnel are encouraged to attend to verify their badges and become familiar with the facility.

- **RPD Staff to host meeting with The Fertilizer Institute (TFI):** On October 2, in Washington, DC, the Radiation Protection Division will host a meeting with the Fertilizer Institute (TFI). TFI

is developing a risk assessment addressing the use of phosphogypsum as a road base. If approved, this risk assessment could be used to support an application for use of phosphogypsum under the Subpart R NESHAP.

To view previous editions of the ORIA Weekly, click here

Thank you

Candice M. Marbury, Special Assistant
OAR/ORIA/IO
U.S. EPA
1301 Constitution Ave, NW
Mail code: 6601T
Washington, DC 20004
Tel: (202) 343-9861
Fax: (202) 343-2395

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 9/25/2019 2:04:14 PM
To: White, Rick [White.Rick@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
CC: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: FW: REMINDER: Entries for the ORIA weekly

On Wednesday, October 2, RPD will host a meeting with the Fertilizer Institute (TFI). TFI is developing a risk assessment addressing the use of phosphogypsum as a road base. If approved, this risk assessment could be used to support an application for use of phosphogypsum under the Subpart R NESHAP. Representatives of CMWR, CST, and CRIO will participate.

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Wednesday, September 25, 2019 8:25 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: FW: REMINDER: Entries for the ORIA weekly

Jon: TFI

If you have not already, please submit an item for the weekly on the TFI meeting. Make sure you copy Rick, as Stefanie is on travel through the end of the week.

Also, please provide Patricia with a list of expected attendees so that she can coordinate with security. Do we need an agenda?

Thanks.

Dan

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, September 24, 2019 4:01 PM
To: OAR-ORIA-RPD <OARORIARPD@epa.gov>
Subject: REMINDER: Entries for the ORIA weekly

This is a reminder to please submit any items for the ORIA Weekly by noon tomorrow.

Thanks!
Stefanie

From: Bacon, Stefanie
Sent: Monday, September 23, 2019 8:00 AM
To: OAR-ORIA-RPD <OARORIARPD@epa.gov>
Subject: Entries for the ORIA weekly

Please send Rick only any items that you have for the ORIA Weekly no later than noon on Wednesday, September 25. I will be out of the office, and will not see your message if you send your entry only to me.

Ideally, we'd like to feature events from the following time periods:

Events that recently took place: September 21 – September 27
Upcoming events: September 28 – October 4

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 7/11/2019 2:00:31 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: Road trip...

Tom asked Phil for something, but I haven't seen anything yet. Here's a placeholder caption:

Phil Egidi and Jon Walsh of RPD and AAAS Fellow Joe Rustick take time out from the HPS Annual Meeting in Orlando to visit a phosphogypsum stack. RPD will meet with The Fertilizer Institute on July 23 to discuss an application for alternate use of phosphogypsum.

From: Bacon, Stefanie
Sent: Thursday, July 11, 2019 9:13 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: Road trip...

Dan,

Do you have an entry I could include with the photo?

From: Bacon, Stefanie
Sent: Wednesday, July 10, 2019 3:47 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>
Subject: RE: Road trip...

Dan,

The picture came through beautifully. Could you please provide some additional text that can go along with the photo for the entry?

Thank you!

From: Schultheisz, Daniel
Sent: Wednesday, July 10, 2019 3:45 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>
Subject: FW: Road trip...

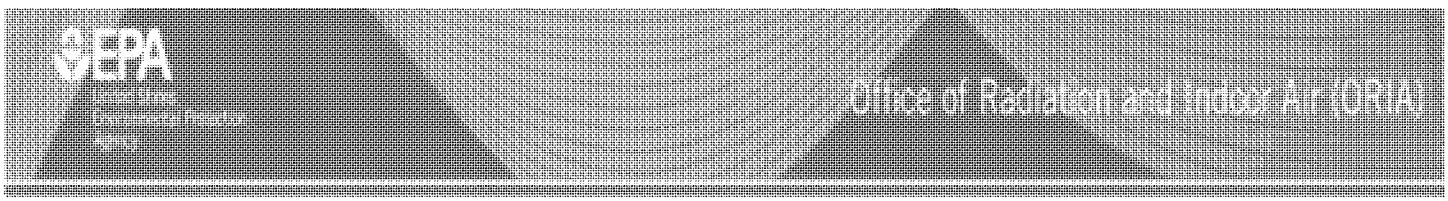
For the weekly.

From: Phil Egidi <pegidi@tds.net>
Sent: Wednesday, July 10, 2019 3:43 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: Road trip...

Sent from my iPhone

Message

From: Marbury, Candice [Marbury.Candice@epa.gov]
Sent: 1/23/2020 8:23:14 PM
To: White, Rick [White.Rick@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Jackson, Scott [Jackson.Scott@epa.gov]; Esher, Diana [Esher.Diana@epa.gov]; Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Stewart, Gretchen [Stewart.Gretchen@epa.gov]; Millett, John [Millett.John@epa.gov]; Shaw, Betsy [Shaw.Betsy@epa.gov]; Febbo, Carol [febbo.carol@epa.gov]; Zhen, Davis [Zhen.Davis@epa.gov]; Perry, Stuart [Perry.Stuart@epa.gov]; Snowbarger, Robert [Snowbarger.Robert@epa.gov]; Lewis, Josh [Lewis.Josh@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]; Rowson, David [Rowson.David@epa.gov]; Smith, Alisa [Smith.Alisa@epa.gov]; Griggs, John [Griggs.John@epa.gov]; Clark, Mike S. [Clark.Michael@epa.gov]; Stafford, Andrea [Stafford.Andrea@epa.gov]; Wilds, Edward [Wilds.Edward@epa.gov]; Idsal, Anne [idsal.anne@epa.gov]; Hoyt, Sarita [Hoyt.Sarita@epa.gov]
CC: Murphy, Stacy [Murphy.Stacy@epa.gov]; Szabo, Stephen [Szabo.Stephen@epa.gov]; Moyer, Michelle [moyer.michelle@epa.gov]; LeSane, Heidi [Lesane.Heidi@epa.gov]; Berry, Mark [Berry.Mark@epa.gov]; Mollsen, Helen [mollsen.helen@epa.gov]; Paguia, Monica [paguia.monica@epa.gov]; Mitchell, Ken [Mitchell.Ken@epa.gov]; Banister, Beverly [Banister.Beverly@epa.gov]; Arnold, David [arnold.david@epa.gov]; McTigue, Erin [McTigue.Erin@epa.gov]; Eagles, Tom [Eagles.Tom@epa.gov]; Childers, Pat [Childers.Pat@epa.gov]; Melanson, Kate [Melanson.Kate@epa.gov]; Jablonowski, Eugene [jablonowski.eugene@epa.gov]; Burke, Dan [Burke.Dan@epa.gov]; Benoit, Eugene [benoit.eugene@epa.gov]; Julien, Rhona [julien.rhona@epa.gov]; Mehta-Sampath, Ameesha [Mehta-Sampath.Ameesha@epa.gov]; Schulingkamp, Cristina [schulingkamp.cristina@epa.gov]; Bolden, Janice [Bolden.Janice@epa.gov]; Blakely, Lashon [Blakely.Lashon@epa.gov]; Batka, Sheila [Batka.Sheila@epa.gov]; Marrero, Jeanette [Marrero.Jeanette@epa.gov]; Aquino, Marcos [Aquino.Marcos@epa.gov]; Barry, Michael [Barry.Michael@epa.gov]; Brozowski, George [brozowski.george@epa.gov]; Generette, Lloyd [Generette.Lloyd@epa.gov]; Honnellio, Anthony [Honnellio.Anthony@epa.gov]; Hooper, Charles A. [Hooper.CharlesA@epa.gov]; Knutson, Lingard [Knutson.Lingard@epa.gov]; Povetko, Oleg [Povetko.Oleg@epa.gov]; Richards, Jon M. [Richards.Jon@epa.gov]; Mahler, Tom [mahler.tom@epa.gov]; Wagner, Christine [Wagner.Christine@epa.gov]; Waldon, MARGARET [Waldon.Margaret@epa.gov]; Hulting, Melissa [hulting.melissa@epa.gov]; Fuoco, Marta [fuoco.marta@epa.gov]; Paguia, Monica [paguia.monica@epa.gov]; Worley, Gregg [Worley.Gregg@epa.gov]; Davis, Amber [Davis.Amber@epa.gov]; Cooper, Artra [Cooper.Artra@epa.gov]; Woodruff, Kevin [Woodruff.KevinL@epa.gov]; Jay, Michael [Jay.Michael@epa.gov]; Algoe-Eakin, Amy [Algoe-Eakin.Amy@epa.gov]; Cooper, Artra [Cooper.Artra@epa.gov]; Payan, Melissa [Payan.Melissa@epa.gov]; Iglesias, Ariel [Iglesias.Ariel@epa.gov]; Siegel, Kathryn [siegel.kathryn@epa.gov]; Perez, Idalia [Perez.Idalia@epa.gov]; Azzam, Nidal [Azzam.Nidal@epa.gov]; McAuley, Jim [mcauley.jim@epa.gov]; MUSANTE, JASON [Musante.Jason@epa.gov]; Godfrey, Althea [godfrey.althea@epa.gov]; Weiss, Benjamin [weiss.benjamin@epa.gov]; Milhollin, Chandler [Milhollin.Chandler@epa.gov]; Freed, Rachel [freed.rachel@epa.gov]; Stoliarova, Janise [Stoliarova.Janise@epa.gov]; Bird, Patrick [Bird.Patrick@epa.gov]; Payan, Melissa [Payan.Melissa@epa.gov]; Walters, Margaret [Walters.Margaret@epa.gov]; Spenillo, Justin [Spenillo.Justin@epa.gov]; Vaupel, Claudia [Vaupel.Claudia@epa.gov]; Reynolds, Mary [Reynolds.Mary@epa.gov]
Subject: ORIA Weekly - The Week Ending January 24, 2020
Attachments: ORIA Weekly Jan 24 2020.docx



ORIA Weekly – January 24, 2020

RECENT EVENTS

- **IED's Rowson Participated in an IAQ Interview for Native America Calling:** On January 21, IED's Dave Rowson participated in a live radio interview hosted by Native America Calling. This broadcast hosts national conversations about issues specific to Native communities and is designed to improve the quality of life for Native Americans. Native America Calling is heard on nearly 70 public, community and tribal radio stations in the United States and in Canada. The focus of this week's program was tribal indoor air quality. Additional panelists were Wilfred Nabahe, chairman of the National Tribal Air Association and Priyanka Pathak, a public health professional and former EPA Region 9 indoor air quality lead.

- **IED's Hurst Participated in the International Builders' Show** – See 1/17/20 ORIA Weekly for more details.

- **IED's Johnson Attended the Energy-Efficient Economy Conference on Health, Environment, and Energy** – See 1/17/20 ORIA Weekly for more details.

- **RPD's Santillan Spoke at the University of North Carolina (UNC) and Toured Duke University's Triangle Universities Nuclear Laboratory (TUNL):** On January 23-24, in Chapel Hill, NC, RPD's Jay Santillan met with UNC students and faculty and presented a talk during the UNC weekly colloquium. Jay's talk was entitled "Regulatory Perspectives on Actinide Geochemistry at the Waste Isolation Pilot Plant Radioactive Waste Facility, Carlsbad, New Mexico, USA." Santillan also traveled to Durham, NC to visit with students and faculty at Duke University and to tour the TUNL facility.

- **RPD Staff Met with The Fertilizer Institute (TFI):** On January 23-24, in Washington, DC, RPD staff will meet with representatives of the Fertilizer Institute (TFI), which represents producers of phosphate fertilizer. Meetings discussed TFI's risk assessment and application to use phosphogypsum in road construction. The Thursday meeting will focus on technical issues, and the Friday meeting on legal and policy issues.

RadNet Report for the Week of January 13, 2020

Overall monitor operational percentage was 89.7%. This is above the operational goal of 80%.

UPCOMING EVENTS (As of January 24)

Radiation Protection and Emergency Response

- **RPD's Feltcorn to Conduct Evaluation of Tier 1 Request:** On January 27-29, near Idaho Falls, ID, RPD's Ed Feltcorn, of the Waste Isolation Pilot Plant (WIPP) Waste Characterization Inspection Team, will conduct an evaluation of a Tier 1 request to add a waste stream stored at the Naval Reactors Facility at the Idaho National Laboratory. This evaluation will determine if the waste is compliant with 40 CFR 194 requirements.

- **ORIA Staff to Attend Health Physics Society (HPS) Midyear Technical Meeting:** On January 27-29 in Bethesda, MD, RPD staff will attend the HPS midyear technical meeting. ORIA Office Director Jon Edwards will speak for the opening session and staff members David Stuenkel, Angela Shogren, Gary Chen and Jessica Wieder will give talks, present a poster and/or chair sessions at the meeting. Staff members Jon Nagata, Brian Littleton, Lowell Ralston, Jon Walsh, Phil Egidi and Sara DeCair will participate in technical sessions on the latest in health physics research, applications and policy.

- **RPD's Snead to Attend International Atomic Energy Agency (IAEA) Workshop on the Arrangements for the Termination of a Nuclear or Radiological Emergency:** On January 27-31, in Ottawa, Canada, RPD's Kathryn Snead will represent USEPA at the North American regional IAEA Workshop on Arrangements for the Termination of a Nuclear or Radiological Emergency. The workshop will discuss arrangements needed to ensure the smooth and timely resumption of normal social and economic activity after a nuclear or radiological emergency.

- **RPD's Hallam to Attend Mars 2020 Radiological Contingency Planning (RCP) Meeting:** On January 28-30, in Cape Canaveral, FL, RPD's Chris Hallam will participate in the fourth of a series of Radiological Contingency Planning events to support NASA's Mars 2020 mission which will employ a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) containing plutonium. The meeting is designed to foster interagency coordination for the scheduled launch in July 2020, and will be attended by Federal, state and local stakeholders. The meeting will review the results of the November 2019, Command Post Exercise, conduct a review of updated plans, procedures, and checklists, and solidify the deployment schedule for agencies actively participating in the launch.

Indoor Air Quality

- **IED's Mitchell To Participate in the annual Engineers in Technical and Humanitarian Opportunities of Service (ETHOS) Conference:** On January 24-26, in Seattle, WA, IED's John Mitchell will participate in the annual Engineers in Technical and Humanitarian Opportunities of Service (ETHOS) Conference. John will join with more than 100 household energy community members to discuss stove design and performance, laboratory and field-testing results, development and dissemination of cookstove standards, and project activities and research initiatives. John will facilitate sessions on the development and dissemination of cookstove standards through the International Organization for Standardization ISO process. While in Seattle, John will meet with staff from the Gate's Foundation's Global Good initiative to discuss their household energy activities and working together in the coming years.

To view previous editions of the ORIA Weekly, click here

Thank you

Candice M. Marbury, Special Assistant
OAR/ORIA/IO
U.S. EPA
1301 Constitution Ave, NW
Mail code: 6601T
Washington, DC 20004
Tel: (202) 343-9861
Fax: (202) 343-2395

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 8/25/2020 5:24:13 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: FAQ Question 8 - volume and number of stacks

Ex. 5 Deliberative Process (DP)

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Tuesday, August 25, 2020 1:16 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: FAQ Question 8 - volume and number of stacks

It's also a bit confusing, on page 28 of the Revised Petition, TFI says 46 million tons of PG is produced each year.

Then on page 11 of the economic analysis, TFI says:

Ex. 5 Deliberative Process (DP)

-Joe

From: Rustick, Joseph
Sent: Tuesday, August 25, 2020 1:07 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: FAQ Question 8 - volume and number of stacks

Ex. 5 Deliberative Process (DP)

-Joe

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Tuesday, August 25, 2020 8:10 AM
To: Rustick, Joseph <rustick.joseph@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: FAQ Question 8 - volume and number of stacks

Ex. 5 Deliberative Process (DP)

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Monday, August 24, 2020 5:28 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: FAQ Question 8 - volume and number of stacks

Hi Dan,

Ex. 5 Deliberative Process (DP)

Thanks,

Joe

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, August 24, 2020 10:22 AM
To: Rustick, Joseph <rustick.joseph@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: FAQ Question 8 - volume and number of stacks

Ex. 5 Deliberative Process (DP)

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Monday, August 24, 2020 10:19 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: FAQ Question 8 - volume and number of stacks

Hi Dan,

Ex. 5 Deliberative Process (DP)

Best,

-Joe

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, August 24, 2020 9:35 AM
To: Rustick, Joseph <rustick.joseph@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: FAQ Question 8 - volume and number of stacks

Joe and Stefanie:

Ex. 5 Deliberative Process (DP)

Thanks.

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 9/23/2020 5:06:59 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: FW: Final TFI package
Attachments: Action Memo TFI Petition Approval Austin to Wheeler Sept 21 2020.docx; CQR072.pdf; FR Typesetting TFI_.pdf; NESHAP Subpart R Approval TFI Request Other Use Phosphogypsum FRN_09212020.docx; TFI Approval Action Information Form 9-21-2020 .doc; TFI approval letter on AD Letterhead Sept 21 2020.docx; TFI response-Comms Plan_09 21 2020 .docx; TFI response-Press Release_09 21 2020 .docx; TFI_Approval_1-pager_9-21-2020 .docx; Transmittal memo Edwards to Austin TFI PG Request 9212020.docx

FYI

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, September 21, 2020 5:30 PM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Cc: Cherepy, Andrea <Cherepy.Andrea@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; White, Rick <White.Rick@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; Holden, Patricia <Holden.Patricia@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>; Marbury, Candice <Marbury.Candice@epa.gov>
Subject: Final TFI package

Hi Jon,

Ex. 5 Deliberative Process (DP)

Let me know if you need any further help. We'll be using Adobe electronic signatures. If you could, please add in the date for the transmittal memo before adding your signature. Thanks

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 1/13/2020 2:40:41 PM
To: Egidi, Philip [Egidi.Philip@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: NESHAP & TFI Administrative | Standing Meeting

Ex. 5 Deliberative Process (DP)

From: Egidi, Philip <Egidi.Philip@epa.gov>
Sent: Monday, January 13, 2020 9:24 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: NESHAP & TFI Administrative | Standing Meeting

Please send me a link to the Sharepoint site, I need to upload some stuff.
Thanx
PVE

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Monday, January 13, 2020 7:04 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: NESHAP & TFI Administrative | Standing Meeting

Stef is teleworking, so let's just do Skype.

I'll update you on last Thursday's lawyerpalooza.

-----Original Appointment-----
From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, October 15, 2019 3:24 PM
To: Bacon, Stefanie; Walsh, Jonathan; Egidi, Philip
Cc: Rustick, Joseph
Subject: NESHAP & TFI Administrative | Standing Meeting
When: Monday, January 13, 2020 10:00 AM-11:00 AM (UTC-05:00) Eastern Time (US & Canada).
Where: DCRoomWest1317

Join Skype Meeting

Trouble Joining? Try Skype Web App

Join by phone

Toll number: Ex. 6 Personal Privacy (PP) (Dial-in Number) English (United States)
Find a local number

Conference ID: Ex. 6 Personal Privacy (PP)
Forgot your dial-in PIN? | Help

.....

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 1/6/2020 7:55:40 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; White, Rick [White.Rick@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
CC: Egidi, Philip [Egidi.Philip@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]
Subject: RE: TFI
Attachments: TFI 1-pager_OAR_1-06-2019_expanded.docx

For 3pm.

-----Original Appointment-----
From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, January 06, 2020 1:47 PM
To: Veal, Lee; Peake, Tom; Schultheisz, Daniel; White, Rick; Walsh, Jonathan; Rustick, Joseph; Bacon, Stefanie
Subject: TFI
When: Monday, January 06, 2020 3:00 PM-3:30 PM (UTC-05:00) Eastern Time (US & Canada).
Where: DCRoomWest1424/ORIA

Purpose: Lee would like to meet before the pre-brief with Jon Edwards.

Scheduler
Patricia Holden
202-343-9458

Message

From: Wieder, Jessica [Wieder.Jessica@epa.gov]
Sent: 8/25/2020 1:49:14 AM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: TFI Comms Plan
Attachments: TFI Communications Plan_8-21 jw.docx

A little later than COB, but still before tomorrow.

Give me a call tomorrow if you want to discuss any of the suggestions. This is a very well thought through comms plan. You and Joe did an EXCELLENT job!

Ex. 5 Deliberative Process (DP)

Jess

Jessica Wieder
Director, Center for Radiation Information and Outreach
U.S. Environmental Protection Agency
Radiation Protection Program
w: 202-343-9201
c: 202-420-9353

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 9/21/2020 6:52:46 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: FW: TFI Materials for Your Review
Attachments: Action Memo TFI Petition Approval Austin to Wheeler Sept 18 2020.docx; TFI approval letter on AD Letterhead Sept 18 2020.docx; transmittal memo Edwards to Austin TFI PG Request 9-18-2020.docx

FYI

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, September 21, 2020 2:34 PM
To: Holden, Patricia <Holden.Patricia@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: FW: TFI Materials for Your Review

Hi Patricia,

Jon has cleared on the TFI package. Could you please take your editorial pen to these memorandum/letter documents, adding letterhead where needed and formatting properly? Send them back and then I can get you the whole package including that long list below for submission to CMS. We're not quite ready for CMS yet, however, so no need to look at that today.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Friday, September 18, 2020 3:15 PM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Subject: TFI Materials for Your Review

Jon:

Attached for your review are the components of the package for approval of the TFI request for other use of phosphogypsum. Files include:

1. Transmittal Memo from you to Anne Austin, recommending that she forward the package to the Administrator;
2. Action Memo from Anne to the Administrator, recommending his signature on the approval letter and Federal Register notice;
3. Letter from the Administrator to TFI approving the request;
4. Federal Register package, including;
    - Federal Register notice for Administrator signature;
    - Typesetting request and screenshot of funding information from Compass;

    - Action Information form;
5. 1-page summary (similar to the document provided for the Administrator briefing next week);
6. Communications plan; and
7. Press release.

I believe you already have the communications plan and press release, which have also been shared with OAR communications. Charles Starrs (OGC) has provided some comment on these two documents, which will need to be reviewed with CRIO staff. Charles' comments on the other documents have been addressed.

Please let Lee or me know if you have questions or comments. Thanks.

Dan

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 8/24/2020 9:47:58 PM
To: Wieder, Jessica [Wieder.Jessica@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]
CC: Boyd, Mike [Boyd.Mike@epa.gov]; DeCair, Sara [DeCair.Sara@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
Subject: FW: Final approval letter for TFI
Attachments: Response to TFI- Letter PDAA to TFI 08242020.docx

FYI – this is the final letter, or will be very soon.
FR package is next!

Thank you for your contributions toward this project. I very much appreciate it.

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Veal, Lee
Sent: Monday, August 24, 2020 5:45 PM
To: Holden, Patricia <Holden.Patricia@epa.gov>
Cc: Cherepy, Andrea <Cherepy.Andrea@epa.gov>; Edwards, Jonathan <Edwards.Jonathan@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Dan Schultheisz (Schultheisz.Daniel@epa.gov) <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: Final approval letter for TFI

Hi Patricia,

Would you please put this letter into a final form suitable for routing and final signature? It is on electronic letterhead at present but please confirm that it comports with EPA correspondence standards. Thank you in advance.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Lee, Raymond [Lee.Raymond@epa.gov]
Sent: 10/14/2020 7:16:56 PM
To: Veal, Lee [Veal.Lee@epa.gov]
CC: Peake, Tom [Peake.Tom@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Tong, Xinyue [Tong.Xinyue@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; White, Rick [White.Rick@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: FW: Administrator digitally signed: The Fertilizer Institute (TFI) Phosphogypsum Letter & FR Notice
Attachments: Fertilizer.Institute.SIGNED.pdf; 10014-36-OAR NESHAP Subpart R Approval TFI Request Other Use Phosphogypsum FRN_09212020 mvf edits 10.6.20_Admin.pdf

FYI – includes the signed FR notice as well. No word yet on pub date but will keep you all posted.

From: Morgan, Ruthw <morgan.ruthw@epa.gov>
Sent: Wednesday, October 14, 2020 2:40 PM
To: Campbell, Ann <Campbell.Ann@epa.gov>
Cc: Pritchard, Eileen <Pritchard.Eileen@epa.gov>; Millett, John <Millett.John@epa.gov>; DeLuca, Isabel <DeLuca.Isabel@epa.gov>; Gaines, Cynthia <Gaines.Cynthia@epa.gov>; Shoaff, John <Shoaff.John@epa.gov>; Lubetsky, Jonathan <Lubetsky.Jonathan@epa.gov>; Mcquilkin, Wendy <Mcquilkin.Wendy@epa.gov>; Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>
Subject: Administrator digitally signed: The Fertilizer Institute (TFI) Phosphogypsum Letter & FR Notice

Good afternoon,

Today, the Administrator digitally signed: The Fertilizer Institute: Phosphogypsum Letter and FR Notice.

If you have any questions about this email, please let me know. Thanks!

Ruthw Morgan, Special Assistant
Office of the Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Ave., NW
Washington, DC 20460
(202) 564-1326
Morgan.Ruthw@epa.gov

6560-50-P

ENVIRONMENTAL PROTECTION AGENCY

[EPA-HQ-OAR-2020-0442; FRL–10014-36-OAR]

Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute

AGENCY: Environmental Protection Agency (EPA).

ACTION: Notice.

SUMMARY: The Environmental Protection Agency (EPA) is approving, subject to certain conditions, a request by The Fertilizer Institute for use of phosphogypsum in government road projects. This decision and supporting information is being made available to the public through this notice. Under the Clean Air Act, the EPA may approve a request for other use of phosphogypsum if it determines that the proposed use is at least as protective of human health as placement in a stack, which is the designated management method. With this approval, and in accordance with its terms and conditions, government entities may use phosphogypsum for road construction projects.

DATES: [Insert date of publication in the Federal Register.]

FOR FURTHER INFORMATION CONTACT: Jonathan P. Walsh, Radiation Protection Division, Office of Radiation and Indoor Air, Mail Code 6608T, Environmental Protection Agency, 1200 Pennsylvania Ave., NW, Washington, DC 20460; telephone number: (202) 343-9238; fax number: (202) 343-2304; email address: walsh.jonathan@epa.gov.

Organization of this document. The information in this notice is organized as follows:

I. General Information

A. How Can I Get Copies of This Document and Other Related Information?

II. Background and Overview of Decision

A. The EPA's 1992 Risk Assessment

B. Request by The Fertilizer Institute

C. TFI's Risk Assessment

D. Terms and Conditions of the Approval

SUPPLEMENTARY INFORMATION:

I. General Information

A. How Can I Get Copies of This Document and Other Related Information?

1. *Docket.* The EPA has established a docket for this action under Docket ID No. EPA-HQ-OAR-2020-0442. Publicly available docket materials are available either electronically through www.regulations.gov or in hard copy at the Air and Radiation Docket in the EPA Docket Center, (EPA/DC) EPA West, Room 3334, 1301 Constitution Ave., NW, Washington, DC. The EPA Docket Center Public Reading Room is open from 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding legal holidays. The telephone number for the Public Reading Room is (202) 566-1744, and the telephone number for the Air and Radiation Docket is (202) 566-1742.

2. *Electronic Access.* You may access this Federal Register document electronically from the Government Printing Office under the "*Federal Register*" listings at FDSys (http://www.gpo.gov/fdsys/browse/collection.action?collectionCode=FR).

II. Background and Overview of Decision

Phosphogypsum stacks are large piles of waste from wet acid phosphorous production. There are more than 60 stacks of phosphogypsum located in 13 different states. The majority of these stacks are located in the southeastern region of the United States. Because the phosphate ore used to produce the phosphoric acid contains relatively high concentrations of uranium and radium, phosphogypsum stacks also contain high concentrations of these elements. The presence

of radium in the stacks causes them to release radon gas into the atmosphere.

The EPA regulates the management of phosphogypsum based on its elevated levels of radium and its decay products, including radon gas, which is classified as a hazardous air pollutant under the Clean Air Act. As required by 40 CFR part 61, subpart R (hereafter "Subpart R"), phosphogypsum must be disposed of in engineered piles, called stacks, with the exception of limited use for agricultural and research purposes. In addition, applicants may request approval of other uses of phosphogypsum by following the process prescribed in 40 CFR 61.206.

A. The EPA's 1992 Risk Assessment

The EPA initially established the requirement that phosphogypsum be placed into stacks without any exceptions (54 FR 51674, December 15, 1989). In response to petitions for reconsideration, the EPA re-evaluated the risks of selected applications of phosphogypsum against the risks from stacking (57 FR 23305, June 3, 1992).[1] The EPA determined that the use of phosphogypsum in limited agricultural and indoor research activities could be as protective of human health, in the short- and long-term, as stacking. These approved uses were incorporated into Subpart R at 40 CFR 61.204-205.

The EPA also assessed the use of phosphogypsum in road construction. While the risks were found to be acceptable from most of the exposure scenarios analyzed, the potential risks to residents of dwellings constructed on an abandoned road were calculated to be unacceptably high. The EPA therefore did not approve road construction as a categorical use of phosphogypsum. The EPA did, however, define in 40 CFR 61.206 a process to request approval of other uses of phosphogypsum, including a risk assessment demonstrating that the proposed use is at least as protective of human health, in the short- and long-term, as placement in a stack.

[1] 'Potential Uses of Phosphogypsum and Associated Risks: Background Information Document," EPA 402-R92-002, May 1992.

As stated in the preamble to the final rule, the measure of protectiveness is lifetime risk of fatal cancer to individuals. In connection with the removal of phosphogypsum from stacks for authorized uses, the EPA incorporated sampling, certification, and record-keeping requirements into Subpart R at 40 CFR 61.207 through 61.209.

B. Request by The Fertilizer Institute

On October 15, 2019, The Fertilizer Institute (TFI) submitted its initial "Request for Approval of Additional Uses of Phosphogypsum Pursuant to 40 CFR 61.206," requesting that EPA approve the use of phosphogypsum in road construction. Subsequently, on April 7, 2020, TFI submitted, on behalf of its members that own or operate phosphogypsum stacks, a revised request: "Revised Request for Approval of Additional Uses of Phosphogypsum Pursuant to 40 CFR 61.206: Use in Road Construction Projects Authorized by Federal, State and Local Departments of Transportation or Public Works".

TFI requested that phosphogypsum be approved specifically for government road projects authorized by federal, state and local Departments of Transportation (DOT) or Public Works (PW), and conducted as part of a government road project using appropriate, generally accepted road construction standards and specifications such as ASTM,[2] Federal Highway Administration, federal or state DOT standards and specifications, or standards developed or approved in consultation with the appropriate regulatory DOT or PW authorities. Notably, as envisioned by the request, the submitter of the request (TFI) would not be the entity using the phosphogypsum, although its members may supply the phosphogypsum to the end user (i.e., the government agency responsible for the road construction project). To address this situation, the terms and conditions of the approval require that the phosphogypsum supplier (stack owner or

[2] Formerly the American Society for Testing and Materials, now ASTM International.

operator) and the end user each provide information to the EPA, as appropriate, prior to removal of phosphogypsum from the stack.

TFI estimates that the cost of transportation would make the use of phosphogypsum uneconomical at distances greater than about 200 miles from a stack.[3] In that case, the regional distribution of phosphogypsum stacks suggests that its use for road construction would likely be concentrated in the southeastern part of the country but could also occur in western states such as Idaho and Wyoming.

C. TFI's Risk Assessment

As required by Subpart R, TFI submitted a risk assessment as part of its request.[4] The risk assessment assessed potential exposures to individuals in various scenarios involving road users, nearby residents, and road construction workers. TFI's exposure scenarios and modeling approaches were largely consistent with the EPA's 1992 analysis, as were the overall results.

The EPA finds TFI's risk assessment to adequately demonstrate that the use of phosphogypsum in road construction will be at least as protective of human health, in the short- and long-term, as stacking.[5] However, as in 1992, the EPA remains concerned about potential exposures should the road become abandoned, particularly for a residence built on road material containing phosphogypsum. The EPA does not agree that TFI's assumptions in its analysis of this scenario, such as the use of radon resistant home construction techniques, could be relied upon to limit the potential risks to a future residential individual from such an occurrence. In this case, however, the EPA believes that this risk can be acceptably mitigated by including

[3] "Economic Analysis of Phosphogypsum Reuse," prepared for TFI by Policy Navigation Group, submitted as Appendix 6 to TFI's Revised Request, December 2019, page 19.
[4] "Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum," prepared for TFI by Arcadis Canada Inc., submitted as Appendix 2 to TFI's Revised Request, October 2019.
[5] "Review of the Radiological Risk Assessment Submitted in Support of Request for Approval of Other Use of Phosphogypsum," October 2019, The Fertilizer Institute.

appropriate terms and conditions in the approval.

In defining its request and exposure scenarios, TFI's risk assessment assumes certain limitations involving the construction and placement of roads. For example, phosphogypsum incorporated into the road base and the road surface is limited in its radium-226 concentration and is assumed to be mixed with other materials in limited proportions. The terms and conditions of the approval reflect these assumptions and limitations.

D. Terms and Conditions of the Approval

The EPA has determined that, subject to the terms and conditions summarized below, phosphogypsum may be removed from stacks and used in government road projects, as requested by TFI. This approval to use phosphogypsum in road construction does not authorize the removal of any phosphogypsum from any stacks or the use of any phosphogypsum for road construction unless and until the information required by the "Initial Conditions," below, is provided to EPA. Only after such information is provided to EPA, may phosphogypsum be removed from stacks and used in road construction, further provided that the conditions expressed in "Other Conditions," below, continue to be met. A complete listing of the terms and conditions applicable to this approval may be found in the approval letter.[6] Additional supporting documentation, such as the complete TFI request and risk assessment, are also in the docket.

1. Initial Conditions

Prior to the distribution and/or use of phosphogypsum for any government road project, the owner or operator of the stack from which phosphogypsum is to be distributed or the governmental entity responsible for building and maintaining the road, as appropriate, must submit to the Agency all information required by 40 CFR 61.206(b), as more specifically

[6] Letter from Andrew Wheeler, Administrator, Environmental Protection Agency, to Corey Rosenbusch, President and CEO, The Fertilizer Institute, Docket No. EPA-HQ-OAR-2020-0442.

described in the approval letter.

2. Other Conditions[7]

Subsequent to the provision of the initial required information to EPA, phosphogypsum may be used in government road projects in accordance with additional conditions, as stated in the approval letter, including, for example, conditions related to:

- Continued control, maintenance, and use of the road;
- Sampling, certification, and record-keeping requirements in 40 CFR 61.206(d) and 61.207 through 61.209;
- Construction of the road consistent with the assumptions, scenarios, limitations, and parameters analyzed in TFI's risk assessment, including an average radium content of no more than 35 pCi/g, no more than 2.25% PG by weight in surface pavement and no more than 50% PG by weight in the road base; and
- Notification and availability of information for the public and road construction workers on the use of phosphogypsum in the road project.

Any use of phosphogypsum not consistent with the terms and conditions and any other limitations set forth in this approval shall be construed as unauthorized distribution of phosphogypsum and may constitute a violation of or noncompliance with 40 CFR part 61, subpart R. This approval is pursuant to Subpart R promulgated under the authority of the Clean Air Act. This approval does not relieve TFI, phosphogypsum stack owners or operators or

[7] In addition to the information required by 40 CFR 61.206(b), as noted in connection with the "Initial Conditions," the "Other Conditions" include conditions associated with the requirements of 40 CFR 61.206(d) and 61.207-61.209; conditions inherent in the nature of or limitations or assumptions associated with TFI's request; and conditions imposed under the EPA's authority and discretion under 40 CFR 61.206(e). The EPA believes that these conditions are either required by 40 CFR part 61, subpart R or are reasonably appropriate to help provide continued assurance that the use is at least as protective as disposal of phosphogypsum in stacks and will ensure that the removal of phosphogypsum from stacks and use in government road projects will be consistent with TFI's request and will occur with public notice and appropriate information availability.

resellers, retailers, distributors, or end users or other entities handling, processing or using phosphogypsum of responsibility to comply with other applicable laws and regulations.

Andrew Wheeler,
Administrator.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

October 14, 2020

THE ADMINISTRATOR

Mr. Corey Rosenbusch
President and Chief Executive Officer
The Fertilizer Institute
425 Third Street, SW, Suite 950
Washington, D.C. 20024

Dear Mr. Rosenbusch:

The Fertilizer Institute, on behalf of its members that own or operate phosphogypsum stacks, has asked the U.S. Environmental Protection Agency to approve, under 40 C.F.R. § 61.206, the removal of PG from required stacks for use in government road construction projects. As discussed below, the EPA grants the request subject to certain conditions.

Background

On October 15, 2019, TFI submitted its initial "Request for Approval of Additional Uses of Phosphogypsum Pursuant to 40 C.F.R. § 61.206," requesting that the EPA approve the use of PG in road construction. Subsequently, on April 7, 2020, TFI submitted, on behalf of its members that own or operate PG stacks, a revised request: "Revised Request for Approval of Additional Uses of Phosphogypsum Pursuant to 40 C.F.R. § 61.206: Use in Road Construction Projects Authorized by Federal, State and Local Departments of Transportation or Public Works" (hereinafter the "Revised Request"). In evaluating TFI's submittals, the EPA generally has focused on the revised request, which we understand to be the most recent, complete version of TFI's request. The EPA has, however, evaluated TFI's request in light of all the materials submitted, including information submitted in connection with the initial request, as well as information subsequently submitted. The Revised Request asks the EPA to approve the use of PG in certain road construction projects:

> A determination by EPA, pursuant to 40 C.F.R. § 61.206, that PG containing up to an average of 35 picocuries per gram [pCi/g] may be used in road base, paving, and various combinations of road base and paving in Government Roadway Projects that meet the commitments of this petition and are:
>
> 1. Authorized by federal, state and local Departments of Transportation (DOT) or Public Works (PW), and

2. Conducted as part of a government road project using appropriate, generally accepted road construction standards and specifications such as American Society for Testing and Materials (ASTM), Federal Highway Administration (FHWA), federal or state DOT standards and specifications, or standards developed or approved in consultation with the appropriate regulatory DOT or PW authorities.

Revised Request at 23-24.

TFI submitted or resubmitted a number of materials with the Revised Request, including miscellaneous federal and state road construction specifications and requirements; a Summary of the Risk Assessment (previously submitted by TFI); a Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum prepared by Arcadis Canada Inc. on behalf of TFI (previously submitted by TFI); a technical memorandum prepared by Exponent on behalf of TFI relating to a chemical risk screening to evaluate potential risks associated with metals/metalloids in PG; responses – apparently prepared by Arcadis Canada Inc. on behalf of TFI – to various questions and comments from the EPA; a discussion by TFI of the results of sampling and radiological testing of samples of PG from 10 stacks in four states; an economic analysis by the Policy Navigation Group, on behalf of TFI, to estimate potential regulatory cost savings associated with using PG in road construction; information on the location of certain PG stacks in Florida, Louisiana, Wyoming and Idaho; a list of materials cited in the Revised Request and other items submitted by TFI. These submissions are identified in TFI's Revised Request as Attachment A and Appendices 1 through 8, respectively. Revised Request at 2-3 and Attachment A and Appendices 1-8.

A significant part of the Revised Request and related information submitted by TFI relates to TFI's assessment of the risks associated with the use of PG in road construction. TFI evaluated the risks under various scenarios, including risks to road construction workers, truck drivers transporting PG, road users, utility workers performing work on utilities at or under roads constructed with PG and residents living near roads constructed with PG. TFI assessed risk based on certain identified assumptions about the amount of PG used in road construction projects and on the amount of radium-226 in the PG used in road construction. With the assumptions used in TFI's risk assessment, TFI's calculated risks for the reasonably maximally exposed individual were no more than 0.5 in 10,000, less than the 3 in 10,000 risk that TFI maintains the EPA uses as the risk of the PG if left in the stack. See, for example, Revised Request, at 16 (Table 1). TFI's risk assessment concluded that the risk of using PG in road construction is low and using PG in road construction would be at least as protective as keeping PG in stacks.

The Revised Request notes the requirements of 40 C.F.R § 61.206, including the information that a request for approval of other uses of PG (other than keeping the PG in stacks) must contain. See, for example, Revised Request at 24-25. The Revised Request asserts that it has provided sufficient information for the EPA to determine whether the proposed use would be at least as protective as disposal of PG in stacks, suggesting that it has provided the information required by 40 C.F.R § 61.206(b)(1), (2), and (6)-(9). Revised Request at 50, footnote 123. The Revised Request essentially acknowledges that it has not provided the information required by 40 C.F.R § 61.206(b)(3)-(5) and (10) but suggests that the EPA approval may be "conditioned upon receipt" of such information. *Id.*

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The Revised Request includes discussion of various other considerations that TFI argues weigh in favor of supporting or allowing uses of PG, such as use in road construction, rather than simply requiring that PG be kept in stacks. Among these considerations are the following contentions: there has been significant growth in the industry and resulting significant increases in PG material generated that the EPA did not anticipate when generally requiring that PG be kept in stacks; the number and size of PG stacks have increased, as well as the costs to manage and maintain the stacks; other countries do not strictly require that PG be kept in stacks and more readily allow PG to be used for other purposes; and allowing other uses to be made of PG is consistent with the EPA's interest in "beneficial uses" of materials and with general EPA policies encouraging recycling.

Discussion

The EPA's *Clean Air Act* regulations at 40 C.F.R. Part 61, Subpart R, address concerns about radon emissions from PG. Subpart R generally applies to owners or operators of PG stacks and to "each person who owns, sells, distributes, or otherwise uses any quantity of phosphogypsum." 40 C.F.R. § 61.200. The basic requirement of Subpart R is that PG must be placed in stacks and may not be removed from stacks, except "as expressly provided." 40 C.F.R § 61.202. Subpart R provides three sets of exceptions under which PG may be removed from stacks: PG may be removed from stacks and used "in outdoor agricultural research and development and agricultural field use" under certain circumstances (40 C.F.R § 61.204); PG may be removed from stacks and used "in indoor research and development activities" under certain circumstances (40 C.F.R § 61.205); and, upon request, the EPA may approve the removal of PG from stacks and the use of PG for "other purposes" (40 C.F.R § 61.206). Relying on this "other purpose" approval authority, the Revised Request asks the EPA to approve the removal of PG from stacks for use in government road construction.

As the Revised Request acknowledges, a request for approval of the use of PG for other purposes must contain certain information, including information about the specific location(s) where the PG will be used. 40 C.F.R § 61.206(b)(1)-(10). The procedure also requires that a request be "signed and dated by a corporate officer or public official in charge of the facility." 40 C.F.R § 61.206(b)(10). A request must include, for example, the location – including mailing address – of each "facility" where any use, handling or processing of PG will take place. 40 C.F.R § 61.206(b)(3), (4). The Revised Request has provided the locations of PG stacks owned or operated by TFI member companies, locations where at least some of the use, handling or processing of the PG to be used in road construction may occur. The Revised Request has not, however, provided any specific location information where the ultimate requested use – road construction – will take place. In addition, to the extent that there may be intermediary locations (such as processing facilities or construction yards) between a PG stack and a road under construction with PG, the Revised Request has not identified any such intermediary locations. A request under 40 C.F.R § 61.206 for approval of other use of PG also must include information on the quantity of PG to be used by each "facility." The Revised Request provided information about the percentage of PG likely to be used in either roadbed or pavement but has not provided information on the quantity of PG to be used in each road construction project.

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The Revised Request has provided considerable information about the anticipated use of PG in road construction. The Revised Request has, for example, provided information about the types of roads that may be constructed using PG, how PG may be used and the road construction process. The Revised Request has provided information about the proposed average concentration of radium-226 in the PG to be used. Critically, the Revised Request assessed and estimated risks associated with the use of PG in road construction.

The agency may approve a request to use PG for some "other purpose" if the proposed distribution or use is at least as protective of public health, in the short and long term, as disposal of PG in a stack. 40 C.F.R § 61.206(c). In the event the agency approves a request to remove PG from stacks and use PG for other purposes, certain prescribed requirements must be met, including requirements set out in 40 C.F.R. §§ 61.206(d) and 61.209. These include requirements on the owner or operator of a stack from which PG is removed to determine radium-226 concentrations; on stack owners or operators and on PG sellers or resellers, distributors and end users to ensure proper preparation and maintenance of certification documents; and on end users to prepare and maintain various records. 40 C.F.R §§ 61.206(d) and 61.209. In addition, the EPA has the authority to impose additional terms and conditions. 40 C.F.R § 61.206(e).

Although the Revised Request has not provided complete information about the specific locations where roads will be built using PG and has not identified the specific quantity of PG to be used in road construction, the lengthy, detailed information provided by the Revised Request about using PG in road construction and the thorough risk assessment is sufficient information for the agency to determine whether use of PG in road construction is at least as protective as disposal in a stack, at least under the circumstances and conditions described in the Revised Request and reflected in the risk assessment. In light of the information provided by TFI, the nature of the request and the conditions identified below, the agency concludes that the additional information required as part of a request under 40 C.F.R § 61.206(b) – especially information on specific address locations where the PG may be used – is not essential to making the determination of whether the proposed use of PG would be at least as protective of public health as stacking.

In evaluating risks associated with using PG in road construction, the Revised Request used an average radium-226 concentration of 27 pCi/g. Revised Request at 20 and 51. (The Revised Request also extrapolated that, even if the average radium-226 was as high as 148 pCi/g, the use of PG in road construction would be still be sufficiently protective of public health, and the Revised Request requested a "concentration limit" – that is, the limit on the level of radium-226 that may be in PG used in road construction – of 35 pCi/g. See, for example, Revised Request at 28.) The risk assessment was also based on assumptions that, when PG is used in road bed material, it would comprise no more than 50 percent of the road bed material, by weight (the other material would be "soil"), and, when used in road surface material, PG would comprise no more than 2.25 percent, by weight, of the surface pavement. Revised Request at 19. As noted above, the Revised Request evaluated risks from the standpoint of various exposure scenarios, including exposure of: persons engaged in road construction or transportation of PG (truck drivers); nearby residents (residing no closer than 50 feet from the road); and utility workers. At the EPA's request, the Revised Request also addressed risks to persons living on abandoned, reused or reclaimed roads (the "reclaimer scenario"). Revised Request at 22-23. Under all these scenarios, the Revised Request, as calculated in the TFI risk assessment, indicated that the risks associated with using PG in road construction

would be significantly less than a lifetime risk of fatal cancer from radon emissions of 3 in 10,000 and that using PG in road construction would be at least as protective of public health as disposal of PG in stacks. *Id.*

As initially promulgated, Subpart R required "stacking" and did not authorize alternative uses of PG. In 1992, the EPA amended Subpart R to categorically authorize use of PG for agricultural or research and development purposes under certain circumstances and to establish a procedure to request approval of other uses of PG. See 57 Fed. Reg. 23305 (June 3, 1992). At that time, the EPA considered also categorically authorizing the use of PG in road construction, but the EPA decided not to do so because it concluded that "the use of phosphogypsum in road construction presents an unacceptable level of risk to public health." *Id.* That determination largely was based on a concern about the risks to people living in a house constructed on land where roads built using PG once existed. The EPA did not necessarily foreclose any or all use of PG in road construction, but simply declined, at that time, to categorically authorize – as for agricultural or research and development uses – use of PG in road construction.

The EPA agrees that for purposes of assessing whether other uses of PG will be at least as protective as disposing of PG in stacks or a mine (and consistent with the agency's overall risk management policies), the radiation risk associated with phosphogypsum stacks (or disposing of PG in mines) may be numerically interpreted as a lifetime risk of excess mortality no greater than 3 in 10,000 (3×10^{-4}) for any member of the public. The EPA's review of the Revised Request's risk assessment concludes that the use of PG in road construction, when conducted in a manner consistent with the methods and scenarios described in TFI's application and under the conditions stated herein, will not create risks in excess of this threshold.

Because the risks associated with the "reclaimer scenario" previously were of particular concern to the EPA, the EPA asked TFI to address those risks in its analysis, and the Revised Request specifically addressed that scenario. Although the Revised Request regarded such a scenario as "extreme" and "unlikely," it, nonetheless, examined the risk associated with the scenario and concluded that the risk is low and that using PG in road construction still would be at least as protective as stacking. While the TFI risk assessment indicates the risk to the reclaimer could be as protective as leaving the PG in the stack, the EPA has questioned some of the modeling assumptions used by TFI to generate the estimate for the reclaimer. TFI's risk assessment assumed, for example: the PG concentration under a home would be less than that of the road base; there would be a layer of clean soil between the PG and slab of the house; and there would be a vapor barrier. We do not believe that these assumptions can be relied upon to limit potential risks to a future residential reuser of an abandoned road constructed with PG. The EPA has, however, reevaluated the use of PG in road construction in light of the new information and analysis in the Revised Request and now concludes that the risks associated with the "reclaimer scenario" can be addressed with conditions associated with possible future reuse of roads constructed with PG (as noted below).

In accordance with the discussion, above, and subject to certain qualifications and conditions (stated below), the EPA determines that the Revised Request adequately demonstrates that the use of PG in road construction is at least as protective of public health, in the short and long term, as disposal of PG in stacks, and, subject to the same qualifications and conditions, PG

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may be removed from stacks and used in government road construction, as requested by TFI. Accordingly, subject to the following conditions, PG may be used in government road projects authorized by federal, state and local departments of transportation or public works, and conducted as part of a government road project using appropriate, generally accepted road construction standards and specifications such as ASTM, FHWA, federal or state DOT standards and specifications or standards developed or approved in consultation with the appropriate regulatory DOT or PW authorities. See Revised Request at 23-24.

This approval to use PG in road construction does not authorize the removal of any PG from any stacks or the use of any PG for road construction unless and until the information required by the "Initial Conditions," below, is provided to the EPA. After such information is provided to the EPA, PG may be removed from stacks and used in road construction, provided that the conditions expressed in "Other Conditions," below, continue to be met.

Initial Conditions

Prior to the distribution and/or use of PG for any government road project, the owner or operator of the stack from which PG is to be distributed or the governmental entity responsible for building and maintaining the road (the "end user"), as appropriate, must submit the following information to the agency, in writing, to the attention of the Director, Radiation Protection Division, U.S. Environmental Protection Agency, 1200 Pennsylvania Avenue, NW, Mail Code 6608T, Washington, D.C. 20460, and by email to radiation.questions@epa.gov:

a) Identification of the project and of the responsible government agency, including an authorized point of contact and complete mailing address;
b) Geospatial information describing the location and extent of the road construction project using PG and the physical address or geospatial coordinates of any facility where intermediate handling or processing of the PG will take place. This information may be provided as map coordinates or computer files compatible with geospatial software (e.g. .kml, .gpx, .shp);
c) The total quantity of PG expected to be used in each project, the source of PG (company and stack) and the average concentration of radium-226 in the PG to be used;
d) A description of the measures which will be taken to prevent the uncontrolled release of PG into the environment during transportation, handling and construction; and
e) Written confirmation that the road construction project (inclusive of supporting contractors) will comply with the following conditions set forth in this approval, signed and dated by the public official responsible for the road construction project.

Other Conditions

In accordance with 40 C.F.R § 61.206(d)(1) and 40 C.F.R § 61.207, the owner or operator of a stack from which PG is removed to be used in road construction must determine annually the average radium-226 concentration at the location in the stack from which the PG is removed.

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In accordance with 40 C.F.R § 61.206(d)(2) and 40 C.F.R § 61.208, the owner or operator of a stack from which PG is removed to be used in road construction and any subsequent distributor, retailer or reseller, shall prepare, make available and provide, and retain appropriate certification documentation and any subsequent purchaser or transferee of PG shall receive and retain appropriate certification.

In accordance with 40 C.F.R § 61.206(d)(3) and 40 C.F.R § 61.209, each stack owner or operator and end user facility must maintain appropriate records.

In accordance with the circumstances and qualifications associated with the Revised Request and, especially, the risk assessment performed in connection with the Revised Request, as well as the agency's authority under 40 C.F.R § 61.206(e) to impose terms or conditions:

In addition to other generally applicable engineering specifications, PG may only be used in government road construction (no private road building) of paved roads (no unpaved roads) and the road design must fall within the following limits:

a) Average radium-226 content of PG to be used in road base or pavement must not exceed 35 pCi/g;
b) Pavement may contain no more than 2.25 percent PG by weight;
c) Road base may contain no more than 50 percent PG by weight;
d) Road base containing PG may consist of one lift of up to 25 cm depth and not extend beyond paved areas of the road; and
e) A minimum 50-foot setback is required from the edge of the road to inhabited structures.

Roads constructed with PG may not be abandoned (or otherwise permanently cease to be used as a road) and used for other non-road purposes or uses, including the construction of structures on such former roads.

Any PG that is unused in the road construction or removed as part of road maintenance and not reincorporated into the road base must be returned to the stack.

Records required by 40 C.F.R §61.209(c) must be maintained by the end user facility (i.e. government agency) for the life of the road. The government agency shall make those records available for public review.

Prior to use of PG in a road project, the responsible government agency shall provide public notice that the planned road will use PG. This may occur as part of public outreach processes associated with the road project and must include an opportunity for the public to review road plans and risk assessment materials.

Workers involved in road construction shall be informed that PG contains elevated levels of naturally occurring radionuclides and instructed in proper industrial hygiene.

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Any use of PG not consistent with the limitations set forth in this approval shall be construed as unauthorized distribution of PG and may constitute a violation of or noncompliance with 40 C.F.R. Part 61, Subpart R. This approval is pursuant to Subpart R promulgated under the authority of the *Clean Air Act*. This approval does not relieve TFI, phosphogypsum stack owners or operators or resellers, retailers, distributors or end users or other entities handling, processing or using PG of responsibility to comply with other applicable laws and regulations.

If your staff has further questions, please reach out to Lee Ann B. Veal, Director of the Radiation Protection Division, at veal.lee@epa.gov or (202) 343-9448.

Sincerely,

Andrew R. Wheeler

ED_005285_00000391-00008

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 9/18/2020 7:25:50 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; White, Rick [White.Rick@epa.gov]
CC: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]
Subject: September 18 pm version of the checklist
Attachments: TFI Checklist and Status.docx

FYI,
The items that need to go to the ORIA IO today are with the ORIA IO.

Good work everybody! Thanks for all your efforts!

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

TFI Approval Package Checklist and Status Date: September 18 pm

Item	Status	Who has the pen?
Approval Letter	in ORIA IO review	
Administrator briefing 1 pager	in ORIA IO review	
Federal Register Notice	in ORIA IO review	
Action Memo from Anne Austin to the Administrator	in ORIA IO review	
Need to send an email with the process of signing the FR but need to add the date of letter signing		
Transmittal memo from Jon E to Anne	in ORIA IO review	
TFI Approval 1-pager	in ORIA IO review	
TFI Press Release	in ORIA IO review and a version shared with OAR comms	
TFI Communications Plan		
General use and web pages	in ORIA IO review	
Reserved Q & A for RPD	RPD management	
TFI Approval Action Information Form	in ORIA IO review	
Typesetting request and the accounting screen	Done	
Technical review document	being revised	Jon W and Joe
Road abandonment support document	being finalize	Joe

Message

From: Stuenkel, David [Stuenkel.David@epa.gov]
Sent: 12/20/2019 9:35:49 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]
CC: Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: RE: Sharepoint folder for technical review comments

TFI Review Team:

Ex. 5 Deliberative Process (DP)

Have a Happy Holiday and let me know if you have any questions. (I will be on leave Monday, December 23 – Thursday, December 26, 2019.)

David

David Stuenkel, PhD CHP
EPA / OAR / ORIA / RPD / CST
WJC West, Room 1417E
stuenkel.david@epa.gov
(202) 343-9203

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Friday, December 20, 2019 15:59
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>; Nagata, Jonathan <Nagata.Jonathan@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Santillan, Eugenio-Felipe <santillan.eugenio-felipe@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: Sharepoint folder for technical review comments

Hello everyone,

Ex. 5 Deliberative Process (DP)

Thanks,

Joe

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 8/24/2020 4:27:55 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: Comms Plan Questions

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

-Joe

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, August 24, 2020 12:09 PM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: Comms Plan Questions

Hi Joe,

I'm reviewing initial comments from Jess related to the Comms plan Q&A's.

Can you help me with the following:

Ex. 5 Deliberative Process (DP)

Thank you!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 9/18/2020 7:21:21 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: FW: Latest Documents
Attachments: TFI response-Press Release_9-11(fromLV,Sep18,2020)(CStar-Sep19.2020).docx; TFI response-Comms Plan_9-11-20(fromLV,Sep18,2020)(CStar-Sep18,2020).docx

Stefanie:

Ex. 5 Deliberative Process (DP)

Dan

From: Starrs, Charles <Starrs.Charles@epa.gov>
Sent: Friday, September 18, 2020 2:56 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: Latest Documents

Lee:

Ex. 5 Deliberative Process (DP)

Please do not hesitate to call if you have any questions.

Charles Starrs
Air and Radiation Law Office
Office of General Counsel
U.S. EPA
202-564-1996

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Friday, September 18, 2020 11:35 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>
Subject: Latest Documents

Hi,

Thanks for your comments, edits etc. on the TFI materials. I made the changes that we discussed, updated filenames to today's date, and updated Tom's checklist. That is a helpful tool.

Here is a complete copy of everything, including these items:

Ex. 5 Deliberative Process (DP)

Thanks

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 11/4/2020 4:14:13 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
CC: Hellberg, Dennis [Hellberg.Dennis@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Boyd, Mike [Boyd.Mike@epa.gov]
Subject: RE: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

Jon and Stef,

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Wednesday, November 04, 2020 11:12 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Hellberg, Dennis <Hellberg.Dennis@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; Boyd, Mike <Boyd.Mike@epa.gov>
Subject: RE: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

All,

Ex. 5 Deliberative Process (DP)

Jon

7. how does the EPA estimate the lifetime risk of exposure to the stacks? This is important because the EPA said the relative risk was the same.

Ex. 5 Deliberative Process (DP)

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, November 04, 2020 8:38 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Hellberg, Dennis <Hellberg.Dennis@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; Boyd, Mike <Boyd.Mike@epa.gov>
Subject: RE: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

Thank you to the team!

I have provided our responses to Charles for one final look. I will send to Kati once I get the all clear from Charles.

To answer lee's question on geographic location of the reporter – our reporter is writing for The Sun, a publication based out of Florida.

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Tuesday, November 3, 2020 5:24 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Hellberg, Dennis <Hellberg.Dennis@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; Boyd, Mike <Boyd.Mike@epa.gov>
Subject: RE: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

Hi Stef,

Thank you for this final look. My few comments are below. I modified the last response but kept the content.
Is the Sun media outlet in Florida, Britain or elsewhere?

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, November 03, 2020 4:27 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Hellberg, Dennis <Hellberg.Dennis@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; Boyd, Mike <Boyd.Mike@epa.gov>
Subject: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

Team,

There have been a lot of emails today about The Sun's media request. I have compiled the most up to date versions of all answers that I've seen to date. Please review the answers to all questions below and let me know if any changes are needed.

Thank you,
Stefanie

1. Are the underlying assumptions of risk of death due to radiation exposure based on studies of atomic bomb survivors? If not, where do they get the risk of fatal cancer numbers from?

Ex. 5 Deliberative Process (DP)

2. Why did the EPA not allow for public comment on this rule change? When is public comment required?

Ex. 5 Deliberative Process (DP)

3. By government road projects, does this mean just those with federal funding? Not state or local funding?

Ex. 5 Deliberative Process (DP)

4. Will these applications to the EPA come from the phosphate manufacturers or the governmental entity that wants to use the material in road building?

Ex. 5 Deliberative Process (DP)

5. Has the EPA received any applications yet?

Ex. 5 Deliberative Process (DP)

6. How much of an impact can the EPA estimate have on the problem of gypstack formation? Will manufacturers be taking directly off their existing stack or from new material being generated by the manufacturing plants?

Ex. 5 Deliberative Process (DP)

7. how does the EPA estimate the lifetime risk of exposure to the stacks? This is important because the EPA said the relative risk was the same.

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Wieder, Jessica [Wieder.Jessica@epa.gov]
Sent: 8/24/2020 12:32:27 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: TFI comms plan
Attachments: TFI Communications Plan_8-21 jw.docx

Hi Stefanie - I only made it up to question 14 so far, but wanted to pass this along. I will review the rest by COB today.

My comments through FAQ #14 are attached and very minor.

Jess

Jessica Wieder
Director, Center for Radiation Information and Outreach
U.S. Environmental Protection Agency
Radiation Protection Program
w: 202-343-9201
c: 202-420-9353

Message

From: Diaz, Charlene [diaz.charlene@epa.gov]
Sent: 10/15/2020 4:34:44 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: EPA Press Release on Approval of Other Use for Phosphogypsum

I know! Crazy day☺

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator
Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, October 15, 2020 12:19 PM
To: Diaz, Charlene <diaz.charlene@epa.gov>
Subject: RE: EPA Press Release on Approval of Other Use for Phosphogypsum

Yes, sorry, I have been on calls since we got off of our morning TFI call. The comms plan is attached. Within the comms plan is an extensive Q&A. I leave it up to you if you prefer to pass along the comms plan in full, or if you just want to snip out the Q&A and send that.

From: Diaz, Charlene <diaz.charlene@epa.gov>
Sent: Thursday, October 15, 2020 12:08 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: EPA Press Release on Approval of Other Use for Phosphogypsum

Hi Stefanie,

Will you please provide the document you wanted me to share with the Regions; in addition to the link to the Press Release.

Thanks☺
Charlene

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator

Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, October 15, 2020 8:13 AM
To: Diaz, Charlene <diaz.charlene@epa.gov>
Subject: Re: EPA Press Release on Approval of Other Use for Phosphogypsum

Thank you Charlene!

Sent from my iPhone

On Oct 15, 2020, at 7:32 AM, Diaz, Charlene <diaz.charlene@epa.gov> wrote:

Hi Stefanie,

I will send out the press release.

Jon, please keep in mind that we have a special guest on the call Tuesday, Kathy Held from NRCP. I have only alloted about 15 minutes for roll cal and updates,

Thanks,
Charlene

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator
Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, October 14, 2020 4:55 PM
To: Diaz, Charlene <diaz.charlene@epa.gov>
Cc: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: FW: EPA Press Release on Approval of Other Use for Phosphogypsum

Charlene,

Lee asked if you could please provide the TFI press release below to the regional contacts tomorrow AM (10/15). Lee also expects that this will be discussed on Tuesday's call.

Jon, would you be available to speak for about 10 min on the Tuesday call to provide an update on TFI and today's action?

Thanks!
Stefanie

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Wednesday, October 14, 2020 4:34 PM
To: Starrs, Charles <Starrs.Charles@epa.gov>; Edwards, Jonathan <Edwards.Jonathan@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Cc: OAR-ORIA-RPD <OARORIARPD@epa.gov>
Subject: EPA Press Release on Approval of Other Use for Phosphogypsum

https://www.epa.gov/newsreleases/epa-approves-use-phosphogypsum-road-construction

Tony Nesky
Center for Radiation Information and Outreach
Tel: 202-343-9597
nesky.tony@epa.gov

Message

From: Diaz, Charlene [diaz.charlene@epa.gov]
Sent: 10/15/2020 4:28:42 PM
To: Aquino, Marcos [Aquino.Marcos@epa.gov]; Bhesania, Amy [Bhesania.Amy@epa.gov]; Borries, Samuel [borries.samuel@epa.gov]; Perez, Natalia A. [Perez.Natalia@epa.gov]; Brozowski, George [brozowski.george@epa.gov]; Cooper, Artra [Cooper.Artra@epa.gov]; Davis, Amber [Davis.Amber@epa.gov]; Freed, Rachel [freed.rachel@epa.gov]; Generette, Lloyd [Generette.Lloyd@epa.gov]; Honnellio, Anthony [Honnellio.Anthony@epa.gov]; Hooper, Charles A. [Hooper.CharlesA@epa.gov]; Jablonowski, Eugene [jablonowski.eugene@epa.gov]; McAuley, Jim [mcauley.jim@epa.gov]; Merritt, Steven [Merritt.Steven@epa.gov]; Povetko, Oleg [Povetko.Oleg@epa.gov]; Richards, Jon M. [Richards.Jon@epa.gov]; Schulingkamp, Cristina [schulingkamp.cristina@epa.gov]; Snowbarger, Robert [Snowbarger.Robert@epa.gov]; Wagner, Christine [Wagner.Christine@epa.gov]; Laurita, Matthew [Laurita.Matthew@epa.gov]
CC: Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Griggs, John [Griggs.John@epa.gov]; Clark, Mike S. [Clark.Michael@epa.gov]; Stafford, Andrea [Stafford.Andrea@epa.gov]; Wilds, Edward [Wilds.Edward@epa.gov]; Brozowski, George [brozowski.george@epa.gov]
Subject: PLEASE READ: SMR Rulemaking and TFI Press Release Discussion with the Regions
Attachments: TFI response-Comms Plan_09 21 2020 .docx

Hello all,

We are scheduling a meeting on Monday, October 19, 2020 to discuss the following topics with the Regions:

- SMR Rulemaking – Lee Veal
- TFI Press Release – Jon Walsh/Tom Peake (**Link to Press Release**: https://www.epa.gov/newsreleases/epa-approves-use-phosphogypsum-road-construction)

On the RPP Call on Tuesday, October 20, 2020, we currently have a special guest, Kathy Held, from NCRP presenting on the call; therefore we have decided to have an off schedule meeting with the Regions on **Monday, October 19, 2020 from 2:15pm EST to 3:00pm EST** to allow time to discuss these topics without any time constraints.

Attached to this email you will find the TFI Communications Plan, which has an extensive Q&A, which will probably address some of your questions. If not, in preparation for the meeting on Monday, please send me in advance any questions you may have regarding these topics.

I hope all of you are available to attend the meeting on Monday and I look forward to receiving your questions in advance. Please look for an invite, which will contain the call-in information and the MS Teams link.

If I have mistakenly left someone off of this distribution, please feel free to forward as you find appropriate.

Thank you in advance,
Charlene

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator
Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 8/21/2020 8:06:18 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: TFI Q&A

Ex. 5 Deliberative Process (DP)

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, August 21, 2020 4:06 PM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: TFI Q&A

Ex. 5 Deliberative Process (DP)

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Friday, August 21, 2020 4:03 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: TFI Q&A

Hi Stef,

Ex. 5 Deliberative Process (DP)

Thanks,

Joe

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, August 21, 2020 3:18 PM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: TFI Q&A

No worries, that plan sounds perfect!

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Friday, August 21, 2020 3:17 PM

To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: TFI Q&A

Hi Stef,

Sorry I've been working on it but got pulled away a few times today. I'm going through it one last time to check for any final edits, I'll get it to you in the next 30 minutes.

-JOe

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, August 21, 2020 3:12 PM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: TFI Q&A

Hi Joe,

Did you have a chance to look through the TFI Q&A? I promised I would get Jess a draft Comms plan today to review, and I'd love to include the Q&A since it is such a big part of the overall plan.

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 10/15/2020 4:13:59 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]
CC: White, Rick [White.Rick@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: RE: Answers to E&E Media Inquiry for Your Approval: Requested deadline is noon (Politico has no deadline, will send separately)

Tony,

Ex. 5 Deliberative Process (DP)

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Thursday, October 15, 2020 11:46 AM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: Answers to E&E Media Inquiry for Your Approval: Requested deadline is noon (Politico has no deadline, will send separately)
Importance: High

Dear Lee:

Per our discussion in the Teams meeting this morning, draft answers to the E&E inquiry are below for your approval. Please review and make any changes necessary. Deadline is noon; it would be nice if we could make it. (Deadline for Politico is whenever, as they ran their story. I'll send the Politico answers in a separate email)

You may wish to review the webpages before reviewing the answers below. Here are the links: you will need be logged in to the VPN, and you will be prompted for

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Subject: Media Inquiry: E&E re Phosphogypsum
Good afternoon,

DDL: noon, 10/15

1. Why can the 10 pCi/g radium content limit outlined in Subpart R of 40 CRF part 61 now be surpassed to up to 35 pCi/g with regards to approved road projects?

Ex. 5 Deliberative Process (DP)

2. The prepub federal register announcement refers to a Radiological Risk Assessment and Review of Radiological Risk Assessment by The Fertilizer Institute. I can't find those documents anywhere. Can you send them to me? .

Ex. 5 Deliberative Process (DP)

3. The announcement also refers to a letter from Andrew Wheeler to Corey Rosenbusch, president of The Fertilizer Institute, where I can find a complete list of terms and conditions applicable to this gypsum road approval. It says I can find it at Docket No. EPA-HQ-OAR-2020-0442 but that docket number shows 0 results on regulations.gov. Can you send me that letter please?

Ex. 5 Deliberative Process (DP)

Tony Nesky
Center for Radiation Information and Outreach
Tel: 202-343-9597
nesky.tony@epa.gov

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 8/21/2020 8:05:44 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: FW: TFI Q&A

Ex. 5 Deliberative Process (DP)

Wrong File attached oops.

This is the right one

-Joe

From: Rustick, Joseph
Sent: Friday, August 21, 2020 4:03 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: TFI Q&A

Hi Stef,

Ex. 5 Deliberative Process (DP)

Thanks,

Joe

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, August 21, 2020 3:18 PM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: TFI Q&A

No worries, that plan sounds perfect!

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Friday, August 21, 2020 3:17 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: TFI Q&A

Hi Stef,

Sorry I've been working on it but got pulled away a few times today. I'm going through it one last time to check for any final edits, I'll get it to you in the next 30 minutes.

-JOe

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, August 21, 2020 3:12 PM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: TFI Q&A

Hi Joe,

Did you have a chance to look through the TFI Q&A? I promised I would get Jess a draft Comms plan today to review, and I'd love to include the Q&A since it is such a big part of the overall plan.

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 9/11/2020 2:23:37 PM
To: Emmerson, Caroline [Emmerson.Caroline@epa.gov]
CC: Veal, Lee [Veal.Lee@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; White, Rick [White.Rick@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]; Anderson, Lea [anderson.lea@epa.gov]; Coleman, Cheryl [Coleman.Cheryl@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: Sept 11 version of the TFI approval include OGC Sept 8 edits
Attachments: TFI approval letter on AD Letterhead Sept 11.docx

Hello,
Thank you for the discussion this morning.

Under the assumption that the Administrator will be signing the TFI approval letter, I took the version of the letter I received from Charles Starrs, OGC, on September 8, accepted the edits and put the text on the Administrator's letterhead.

Please edit this version.

Talk to you on Tuesday.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 8/20/2020 8:05:37 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
CC: Rustick, Joseph [rustick.joseph@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; White, Rick [White.Rick@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: Introduction
Attachments: TFI FR_Notice_of_availability_rl.docx; TFI 1-pager_OAR_5-20-2020 rev4.docx; Response to TFI-Draft Conditions Letter AA to TFI August 19.docx; TFI_1-pager_6-15-20_oria draft.docx

Hi Jon,

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Thursday, August 20, 2020 3:43 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: Introduction

Ex. 5 Deliberative Process (DP)

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, August 20, 2020 3:00 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: Introduction

Ex. 5 Deliberative Process (DP)

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: Redacted
www.epa.gov/radiation

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Thursday, August 20, 2020 2:56 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: Introduction

Ex. 5 Deliberative Process (DP)

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, August 20, 2020 2:54 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: Introduction
Importance: High

Hi,

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Thursday, August 20, 2020 12:59 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: Introduction

All,

Here is the updated draft FR notice. It has input from Ray and myself and is ready for initial review by management.

Ex. 5 Deliberative Process (DP)

Thanks,
Jon

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, August 20, 2020 12:29 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: Introduction

All: I'm happy to lend the draft comms plan for some plain language on TFI, expected approval actions, and background related text. Please let me know if the attached is sufficient or if there is any other support that I can lend. Note that highlighted sections in the attached will need to be reviewed to ensure consistency between the comms plan, FR, and letter coming from Anne.

I hope this is helpful,
Stefanie

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, August 20, 2020 12:04 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: Introduction

Jon,

+Jess and Rick

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division

Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Thursday, August 20, 2020 9:56 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Introduction

Lee,

Glad you asked. Ray Lee currently has the pen to help me fill in the routine sections, but I was going to check with Tom and Dan about the content.

The only hard requirement for the notice of availability is a one-paragraph plain language summary statement.

Ex. 5 Deliberative Process (DP)

Jon

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, August 20, 2020 9:47 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: FW: Introduction

FYI

Jon – when you have a moment, please share the draft FR. I understand that you won't be done until Friday, but with your vacation next week, I'd like to see something before COB Friday in case I have questions or need info.

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Veal, Lee
Sent: Thursday, August 20, 2020 9:37 AM
To: Belser, Evan <Belser.Evan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>
Subject: Introduction

Hi Evan,

Ex. 5 Deliberative Process (DP)

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Lee, Raymond [Lee.Raymond@epa.gov]
Sent: 9/9/2020 3:47:52 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]
CC: Rustick, Joseph [rustick.joseph@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: OP's edits to the draft FR
Attachments: TFI FR_Notice_of_availability_Aug 23 pb edits.docx

Hi all,

OP has completed their review of the draft we put into FR Dailies near the end of August. I've attached it to this e-mail; you'll see Stephanie's edits/comments in red. Everything they have is very minor. The docket number (EPA-HQ-OAR-2020-0442) is set and the signature block will have to be updated given the Administrator is now signing the package:

Andrew Wheeler
Administrator

If you have any questions on these edits, just let me know! Otherwise, we should be clear to send the completed package forward after we incorporate these edits and any others that may have come along with the numbers or anything else from OLEM.

Thanks,

Ray

Ray Lee | Center for Radiation Information and Outreach (CRIO) | US EPA | Phone 202.343.9463 | Fax 202.343.2303 | lee.raymond@epa.gov

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 10/15/2020 3:08:47 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]
CC: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: Lots happening on TFI; Lee wants to have you look at two items FW: technical review document and road abandonment document

My apologies,

Tomorrow is indeed Friday.

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Veal, Lee
Sent: Thursday, October 15, 2020 11:04 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: Lots happening on TFI; Lee wants to have you look at two items FW: technical review document and road abandonment document

HI Charles,

Thank you for the feedback on timing. Tom and I were able to connect, as well as Jon Edwards and I.

If you could review the technical document by the end of day tomorrow, Thursday, that would be a wonderful thing. Jon E is on similar timing, maybe even today.

Ex. 5 Deliberative Process (DP)

Tony and Stef,
We are going to need another day for the technical report to clear. It will certainly be complete before the FR is published.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 10:50 AM
To: Starrs, Charles <Starrs.Charles@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: Lots happening on TFI; Lee wants to have you look at two items FW: technical review document and road abandonment document

Charles,
Thanks. For the response.
We would like to put both documents on the web site today if at all possible.
Lee also let me know that Jon E and Andrea will be looking at these documents.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Starrs, Charles <Starrs.Charles@epa.gov>
Sent: Thursday, October 15, 2020 10:48 AM
To: Peake, Tom <Peake.Tom@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: Lots happening on TFI; Lee wants to have you look at two items FW: technical review document and road abandonment document

Tom:

Ex. 5 Deliberative Process (DP)

Charles
202-564-1996

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, October 14, 2020 5:35 PM
To: Starrs, Charles <Starrs.Charles@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: Lots happening on TFI; Lee wants to have you look at two items FW: technical review document and road abandonment document

Charles,
I hope this is more of an FYI for you, but it is up to you to see if you think you need to comment on the attachments.

Ex. 5 Deliberative Process (DP)

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Peake, Tom
Sent: Wednesday, October 14, 2020 5:10 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: technical review document and road abandonment document

Lee,
Attached are the latest versions of the technical review and road abandonment documents (guys, please confirm).

Ex. 5 Deliberative Process (DP)

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 9/9/2020 12:43:08 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: TFI Draft Press Release

Thanks.

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, September 09, 2020 8:43 AM
To: Peake, Tom <Peake.Tom@epa.gov>
Subject: RE: TFI Draft Press Release

Ex. 5 Deliberative Process (DP)

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, September 9, 2020 8:41 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: TFI Draft Press Release

Ex. 5 Deliberative Process (DP)

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, September 09, 2020 8:38 AM
To: Peake, Tom <Peake.Tom@epa.gov>
Subject: RE: TFI Draft Press Release

Thank you Tom ☺ Your edits are very helpful. I'll let others chime in before I go through and accept the changes and resolve the comments.

Stefanie

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, September 9, 2020 8:35 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: TFI Draft Press Release

Stefanie,
I think it is a good press release, but I have some edits.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, September 09, 2020 8:00 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Subject: TFI Draft Press Release

Good morning,

I have worked with Jess to draft a TFI press release.

Ex. 5 Deliberative Process (DP)

Please review and provide any comments.

Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Wieder, Jessica [Wieder.Jessica@epa.gov]
Sent: 8/20/2020 4:08:30 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: TFI - plain language for FR
Attachments: image001.gif; ATT00001.htm; FR_Notice_of_availability.docx; ATT00002.htm

Stef - Is there really a hold up with a plain language summary paragraph for the TFI FR notice ? The Comms plan should include some plain language that we could use to fill this gap. Let me know if you need my help.

Jess

Sent from my iPhone

Begin forwarded message:

> **From:** "Veal, Lee" <Veal.Lee@epa.gov>
> **Date:** August 20, 2020 at 12:03:35 PM EDT
> **To:** "Walsh, Jonathan" <Walsh.Jonathan@epa.gov>, "Peake, Tom" <Peake.Tom@epa.gov>, "Schultheisz, Daniel" <Schultheisz.Daniel@epa.gov>
> **Cc:** "Rustick, Joseph" <rustick.joseph@epa.gov>, "Bacon, Stefanie" <Bacon.stefanie@epa.gov>, "Lee, Raymond" <Lee.Raymond@epa.gov>, "Wieder, Jessica" <Wieder.Jessica@epa.gov>, "White, Rick" <White.Rick@epa.gov>
> **Subject: RE: Introduction**

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 8/18/2020 11:48:13 AM
To: Veal, Lee [Veal.Lee@epa.gov]
CC: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; White, Rick [White.Rick@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
Subject: Let's move the letter up
Attachments: Response to TFI-Draft Conditions Letter AA to TFI August 18.docx

Lee,
Dan and I had a discussion with Charles late yesterday afternoon and he made a revision based on that discussion and the draft we sent him earlier in the day.

In the draft attached I deleted the comments and made a couple of other minor edits. Charles said he was ambivalent about using "pages" in front of the page numbers, but since he deleted them once and they were mostly gone, I just deleted the several remaining but crossed out "pages" and did not put in the word anywhere. I did put in "footnote". ☺ I left the markup so you could see the changes.

I think we are done with it and it is ready for you to do a last look. Jon is coordinating with Ray on the FR notice and the team is finishing the FAQs for Stephanie's communication plan. I let Charles know we would be sending the FR notice to him when we got it ready. We also have the EPA technical review that will need to be reviewed, too, in the next week.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 9/8/2020 8:52:53 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
CC: Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: RE: TFI Communications Plan

Hi Stef,

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, September 08, 2020 3:39 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Subject: RE: TFI Communications Plan

Good afternoon Lee:

Ex. 5 Deliberative Process (DP)

Thank you,
Stefanie

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Tuesday, September 1, 2020 10:43 AM
To: Wieder, Jessica <Wieder.Jessica@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel

<Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: TFI Communications Plan

Hi,

Sorry, I forgot the other two attachments that I note in my comments. These are not intended to be all encompassing treatments of their subjects, but they provide you with some illustration of what I'm saying.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Veal, Lee
Sent: Tuesday, September 01, 2020 10:30 AM
To: Jessica Wieder <Wieder.Jessica@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Dan Schultheisz (Schultheisz.Daniel@epa.gov) <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: TFI Communications Plan

Hi Jess and Stefanie,

Thank you, and the whole team for this comprehensive plan with questions/answers, website information, etc. It looks very good.
I have comments for you in this attached document. I'd like to see the next iteration please.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, August 31, 2020 2:40 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: TFI Communications Plan

Good afternoon Lee,

Below is a SharePoint link to the Fertilizer Institute Communications Plan. This document heavily relied on input from the technical team, and has been reviewed by Jessica, Dan, and Tom. Prior to sending it to you, I addressed most of the comments from earlier reviews, including track changes suggested by previous reviewers. You will notice though, that

there are a small number of comments, placeholders, and reminders that I will need to address before the document is final.

Ex. 5 Deliberative Process (DP)

The next step in the review process would be for Jon and Andrea to review the package. Please let me know if and when you would like me to assist with shepherding the document to them. I would also understand if you wanted to pass it on directly.

Finally, and as always, please let me know if you have any questions.

Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 12/6/2019 3:05:48 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: For Review: Draft TFI Webpage
Attachments: TFI_NOA_FR_notice.doc.docx

Thanks, this looks really good.

Ex. 5 Deliberative Process (DP)

- Jon

Redacted

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, December 05, 2019 2:33 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: For Review: Draft TFI Webpage

Jon:

I provided the draft TFI webpage to Jessica for initial feedback. She had some very good comments. There were only two comments that I couldn't resolve. Could you please see the document in the location below, and address the comments tagged to you?

Ex. 5 Deliberative Process (DP)

Once you've had a chance to review this can go to Dan & Tom.

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Nesky, Anthony [Nesky.Tony@epa.gov]
Sent: 12/2/2020 2:42:20 PM
To: Lee, Raymond [Lee.Raymond@epa.gov]
CC: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: FW: EPA tech summary errata--
Attachments: EPA-HQ-OAR-2020-0442-0018.pdf

Importance: High

Dear Ray:

There was a typo in this document, and some formatting issues from conversion to PDF. I'd like to replace this with a corrected version on the website, but can we do on the Docket?

Tony

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, December 02, 2020 9:24 AM
To: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: FW: EPA tech summary errata

Good morning Tony,

I wanted to ask your opinion on a TFI document that we have posted on the web. Jon noticed a few formatting issues in the attached (please see below). Is this something that you would suggest that we fix in the original document, and then repost to the web and/or docket?

Thank you,
Stefanie

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Monday, November 30, 2020 10:26 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: EPA tech summary errata

Here is what I caught:

On p.5, in "Summary of Results", an error printed because the text refers to Table 1.

Footnotes for Table 2 bleed over the page

The final sentence of page 8 bleeds over, creating a nearly blank page.

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 10/15/2020 1:02:00 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]
CC: Bacon, Stefanie [Bacon.stefanie@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
Subject: RE: Approval of Other Use of Phosphogypsum: Supporting Documents Webpage Requires Your Review and Approval

I'm in.

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Thursday, October 15, 2020 8:58 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Approval of Other Use of Phosphogypsum: Supporting Documents Webpage Requires Your Review and Approval

I should have mentioned that you also have to be logged into the VPN to view this page.

Dan, could you send me your cell phone number? I'm not sure I have it.

Tony

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 8:56 AM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Approval of Other Use of Phosphogypsum: Supporting Documents Webpage Requires Your Review and Approval

Do I need to be in the VPN for this?

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Wednesday, October 14, 2020 11:32 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: Approval of Other Use of Phosphogypsum: Supporting Documents Webpage Requires Your Review and Approval
Importance: High

Dear Jon, Dan, and Tom:

I created a document page with the supporting materials that will appear in the Docket upon publication. It includes a signed copy of Administrator Wheeler's letter, as TFI told Lee they had no problem with our putting on the website. Please review the page to ensure I got everything right, and provide me with any edits. We need to publish this tomorrow morning to answer the press inquiry due at 11 AM. (It will enable us to quickly answer or even avoid further inquiries).

Ex. 5 Deliberative Process (DP)

Thanks for all your help with this.

Tony Nesky
Center for Radiation Information and Outreach
Tel: 202-343-9597
nesky.tony@epa.gov

Message

From: Wieder, Jessica [Wieder.Jessica@epa.gov]
Sent: 12/5/2019 1:18:10 AM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: Draft TFI/Phosphogypsum Web Page
Attachments: TFI website jw.docx

Flag: Follow up

Hi Stefanie – This is a great first draft. I have some questions and comments in the attached document to help get it ready for posting with the FR Notice. A lot of the TFI-specific language will be great to have when a decision is made.

Great work.

Jess

Jessica Wieder
Director, Center for Radiation Information and Outreach
U.S. Environmental Protection Agency
Radiation Protection Program
w: 202-343-9201
c: 202-420-9353

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, December 04, 2019 12:18 PM
To: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: Draft TFI/Phosphogypsum Web Page

Jess,

Attached is a draft template and content for the TFI phosphogypsum webpage. I am providing a preview to you before sending up to Tom and Dan. Please let me know if there are any show stoppers ☺.

Ex. 5 Deliberative Process (DP)

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Wieder, Jessica [Wieder.Jessica@epa.gov]
Sent: 11/30/2020 7:45:57 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: Re: Request for additional information

perfect.

Jessica Wieder
Director, Center for Radiation Information and Outreach
U.S. Environmental Protection Agency
Radiation Protection Program
w: 202-343-9201
c: 202-420-9353

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, November 30, 2020 2:45 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Request for additional information

Thank you Tony.

Jon, I agree with Tony that the response was written well. Could you please coordinate a technical approval from Tom or Dan and then bcc me on the official response? I will make sure that we keep a record of this response along with our other files.

Thank you,
Stefanie

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Monday, November 30, 2020 2:34 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Request for additional information

It's really not a cold call. Jon is listed in the Federal Register as the contact, and as such, can reply directly to the questioner. This is a technical question, so there's no need to involve OPA if the press is not involved.

I think Jon answered the question very well, but given the interest in the topic, Jess and I would recommend that Dan S. or Tom approve all replies before they are sent. Also, we should keep a file of these inquiries and our replies.

Thanks!

Tony

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, November 30, 2020 11:12 AM
To: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: FW: Request for additional information

Tony,

How do we typically handle "cold calls" or in the case below, cold emails ☺ Jon received an email from what seems to be a member of the public. No other affiliation is noted. Is this something that Jon, or Radiation.Questions@epa.gov can reply to, or do we need to loop in OPA?

Thank you,
Stefanie

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Monday, November 30, 2020 10:22 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: FW: Request for additional information

Stef, here is the question and my proposed answer.

Ex. 5 Deliberative Process (DP)

From: Audrey Ford <audreytford@gmail.com>
Sent: Monday, November 23, 2020 8:21 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: Request for additional information

To: Jonathan P. Walsh, walsh.jonathan@epa.gov

Good Evening Mr. Walsh,
On October 20, 2020, EPA published a notice in the Federal Register regarding EPA's "Approval of the Request for Other Use of Phosphogypsum by the Fertilizer Institute". One of the technical documents supporting this approval, posted on

EPA's webpage dedicated to this issue, is titled "Technical Review of The Fertilizer Institute Risk Assessment for Additional Use of Phosphogypsum in Road Base," dated June 10, 2020. Multiple times in this review document, it is suggested that The Fertilizer Institute (TFI) provide further information and/or analysis on specific issues. For example, on page 46, it is recommended that TFI be required to further explore both the groundwater and ingestion of crayfish exposure pathways; on page 45, it is recommended that TFI be requested to revise its reclaimer radon exposure dose calculations, and it is stated that "TFI's evaluation of the Nearest Resident exposure pathways needs to be revised." I am wondering if EPA ever requested these revisions, if TFI ever provided them, and if so, where I might access documentation of those revisions? I have explored all the links included on the EPA's "Approval of Other Uses of Phosphogypsum: Supporting Documents" web page and have been unsuccessful in identifying any such document. Thank you in advance for your time and consideration.

Respectfully,
Audrey Ford

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 9/1/2020 2:43:25 PM
To: Wieder, Jessica [Wieder.Jessica@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
CC: White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: TFI Communications Plan
Attachments: TFI Communications Plan_8-21 jw lv.docx; 1-s2.0-0048969794900027-main.pdf; - PHOSPHOGYPSUM_ SHOULD WE JUST LET IT GO TO WASTE_ PARTS 1 AND 2.pdf

Hi,

Sorry, I forgot the other two attachments that I note in my comments. These are not intended to be all encompassing treatments of their subjects, but they provide you with some illustration of what I'm saying.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Veal, Lee
Sent: Tuesday, September 01, 2020 10:30 AM
To: Jessica Wieder <Wieder.Jessica@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Dan Schultheisz (Schultheisz.Daniel@epa.gov) <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: TFI Communications Plan

Hi Jess and Stefanie,

Thank you, and the whole team for this comprehensive plan with questions/answers, website information, etc. It looks very good.
I have comments for you in this attached document. I'd like to see the next iteration please.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, August 31, 2020 2:40 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan

<Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: TFI Communications Plan

Good afternoon Lee,

Below is a SharePoint link to the Fertilizer Institute Communications Plan. This document heavily relied on input from the technical team, and has been reviewed by Jessica, Dan, and Tom. Prior to sending it to you, I addressed most of the comments from earlier reviews, including track changes suggested by previous reviewers. You will notice though, that there are a small number of comments, placeholders, and reminders that I will need to address before the document is final.

Link to SharePoint:

Ex. 5 Deliberative Process (DP)

The next step in the review process would be for Jon and Andrea to review the package. Please let me know if and when you would like me to assist with shepherding the document to them. I would also understand if you wanted to pass it on directly.

Finally, and as always, please let me know if you have any questions.

Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

[House Hearing, 108 Congress]
[From the U.S. Government Printing Office]

PHOSPHOGYPSUM: SHOULD WE JUST LET IT GO TO WASTE? PARTS 1 AND 2

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HEARINGS

before the

SUBCOMMITTEE ON TECHNOLOGY, INFORMATION
POLICY, INTERGOVERNMENTAL RELATIONS AND
THE CENSUS

of the

COMMITTEE ON
GOVERNMENT REFORM

HOUSE OF REPRESENTATIVES

ONE HUNDRED EIGHTH CONGRESS

SECOND SESSION

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MARCH 15, 2004

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Serial No. 108-191

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http://www.house.gov/reform

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PHOSPHOGYPSUM: SHOULD WE JUST LET IT GO TO WASTE? PART 1

MONDAY, MARCH 15, 2004

House of Representatives,
Subcommittee on Technology, Information Policy,
Intergovernmental Relations and the Census,
Committee on Government Reform,
Bartow, FL.

The subcommittee met, pursuant to notice, at 9:33 a.m., in the West Wing, Southwest Florida Water Management District Headquarters, 170 Century Drive, Bartow, FL, Hon. Adam H. Putnam (chairman of the subcommittee) presiding.

Present: Representative Putnam.

Staff present: Bob Dix, staff director; John Hambel, senior counsel; Ursula Wojciechowski, professional staff member; Juliana French, clerk; and Matthew Joyner, district director.

Mr. Putnam. A quorum being present, this hearing of the Subcommittee on Technology, Information Policy, Intergovernmental Relations and the Census will come to order.

Good morning, and welcome everyone to the subcommittee's first hearing on phosphogypsum. Today's hearing is appropriately entitled, ``Phosphogypsum: Should We Just Let It Go To Waste?''

I want to thank the community for their interest in this issue. As indicated by the wonderful turnout that we have today, this is an issue that is very important, not just to Polk County but to all of central Florida and even beyond that.

Currently there are about 1 billion tons of phosphogypsum stored in 24 stacks in Florida, 21 of those stacks here in central Florida. Thirty million new tons of phosphogypsum are produced every year, and we meet today in the shadows of one of those stacks, one of these gyp stacks, as the locals call them, here in the Southwest Florida Water Management District building.

Phosphogypsum is a byproduct of the chemical processing of phosphate rock mined here in Florida. In 1989, the U.S. Environmental Protection Agency promulgated a rule determining that the commercial product of phosphogypsum was a waste product and banned its use for any purpose whatsoever. From

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that point on, the phosphogypsum has been accumulating all over the State.

The possibility of a catastrophic spill in Manatee County last year raised local and Federal concerns. In 2001 the Mulberry Corp., the owner of the Piney Point Phosphates went bankrupt leaving a plant with unattended stacks of phosphogypsum. Since then, the State of Florida has kept the electricity going at the plant and monitored water levels in the phosphogypsum stacks. Last year, the Florida Department of Environmental Protection was granted Federal permission to discharge more than 500 million gallons of treated wastewater from the Piney Point Plant into Bishop's Harbor in Tampa Bay. EPA and the Department of Environmental Protection insisted that it would not be harmful to marine life and others contended that the solution, while the lesser of two evils, would be less environmentally damaging and more economically sound than a spill. That discharge was estimated to span 19,500 square miles and cost $10 million. Although that cost will be covered by a trust fund that phosphate companies pay for environmental restoration, Florida State government has spent $40 million so far to maintain Mulberry's abandoned plants at Piney Point and in Polk County. The expected maintenance and closing costs will total $170 million which will fully deplete the trust fund.

Scientific research conducted and the results found by various entities support a position that phosphogypsum is not a waste but a potentially valuable commercial product. Conclusive evidence by independent researchers and research councils challenge the claims that use of the product is harmful and suggests that specific applications be reviewed. It can be environmentally safe and economically attractive to use phosphogypsum in a variety of ways serving industry and potentially benefiting the taxpayer. Considering that the environmental dangers of stacking phosphogypsum to the unlikely risks associated with the use of it outweigh the risks of storing it as a waste product. We will examine this question and the environmentally safe, potential uses for phosphogypsum this morning.

This morning's hearing will immediately be followed by our second hearing that will focus on understanding the purported risks of phosphogypsum as determined by the Environmental Protection Agency. Representatives from Florida's State and local government will share their thoughts on the risks and uses of phosphogypsum. And finally we will hear the concerns of a dedicated environmentalist involved with the Tampa Bay estuary program.

Ordinarily I would yield to the ranking member of the subcommittee, Mr. Clay from Missouri, for any opening remarks; however, given that this is a field hearing and not in Washington, we will immediately proceed to witnesses for their testimony.

As is the custom for the Government Reform Committee, we swear in our witnesses, so I would ask the first four panelists and anyone joining you who will provide supporting information to our questions to please rise and raise your right hands.

[Witnesses sworn.]

Mr. Putnam. I note for the record that all the witnesses respond in the affirmative.

We will proceed to our first witness, Mr. Michael Lloyd. Mr. Lloyd is the research director of chemical processing at the Florida Institute of Phosphate Research. He received his chemical engineering degree in 1950 from Clemson University. After graduation he worked in the Chemical Corp. for the U.S. Army and Southern Cotton Oil Co. Before joining the Florida Institute of Phosphate Research in 1982 Mr. Lloyd worked 30

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years for Agrico Chemical Co. serving many roles from foreman to project coordinator and director. He participates in the American Institute of Chemical Engineers and the American Chemical Society. Mr. Lloyd is quite possibly the only person to have direct contact with almost all of the events related to phosphogypsum and the EPA since the Florida Institute of Phosphate Research was formed in 1979. His extensive research on the subject of phosphogypsum is commendable and we look forward to his expert testimony. Welcome to the subcommittee, Mr. Lloyd, and you are recognized.

[The prepared statement of Hon. Adam H. Putnam follows:]

[GRAPHIC] [TIFF OMITTED] T5739.001

[GRAPHIC] [TIFF OMITTED] T5739.002

STATEMENTS OF G. MICHAEL LLOYD, JR., RESEARCH DIRECTOR, CHEMICAL PROCESSING, FLORIDA INSTITUTE OF PHOSPHATE RESEARCH; DR. MALCOLM E. SUMNER, AGRICULTURAL AND ENVIRONMENTAL CONSULTANT, REGENTS' PROFESSOR EMERITUS, UNIVERSITY OF GEORGIA; DR. DOUG CHAMBERS, EXECUTIVE VICE PRESIDENT, DIRECTOR OF RADIOACTIVITY AND RISK STUDIES, SENES CONSULTANTS LIMITED; AND DR. CHIH-SHIN SHIEH, ENVIRONMENTAL CONSULTANT, CS ENVIRONMENTAL SOLUTIONS

Mr. Lloyd. Thank you.

Finding environmentally sound ways to utilize phosphogypsum was an original priority with the Florida Institute of Phosphate Research. One of our first activities was to have an international symposium on phosphogypsum in November 1980. Our efforts looked at three different basic approaches. To use it as a chemical raw material, use it in construction and for agriculture. We did sponsor research to recover the sulfur values but economics made that somewhat impractical. For construction purposes the only thing we really looked at was to use it for road building. Our plan was to build a secondary road first, test it environmentally and for construction purposes and then go ahead and build a primary and later on an interstate type road.

We did build 2 secondary roads, one in Polk County and one up in north Florida in Columbia County. We have tested both of them environmentally and testing continues on the Polk County road even until today. Testing by the Florida Department of Transportation has revealed that the Polk County road has gotten stronger with time rather than getting weaker. It also has shown fewer repairs than what is necessary for other roads.

Phosphogypsum has been tested for all kinds of agriculture. We have used it for truck crops, for grass, and we have also tested for radionuclide uptake by both the cattle and by the grass. We have used it to find out about curing subsurface acidity and we have also used it to improve the water penetration in the soil. One of the other uses we have gotten into is for marine applications, for making glass and for daily cover in municipal solid waste landfills.

Until December 1989, phosphogypsum was sold as a product of commerce in all States of the country. At that time, EPA elected to declare it a waste and forbid its use, including forbidding research. In the time period between 1989 and 1992, EPA developed the risk assessments that are used as the basis for the use ban in the 1992 rule. The 1989 proposed rule did not have any data to support the ban. All of the bans that they have done are based on building a house on either the roadbed or building it on land that was fertilized with phosphogypsum for 100 years. A residency value of 70 years was used to calculate the risk, which is somewhat longer than the values

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used in many EPA risk calculations.

The ban on agriculture was based on averaging the use in California for soil treatment and using it for agriculture in this part of the country. The two uses that were used to get an average are totally unrelated. They are like saying apples and oranges are the same because both of them are fruits. The 1992 rule did allow the use of north Florida phosphogypsum in agriculture and prohibits all other uses. However, you can use EPA's methodology and prove that building roads, using it in a landfill or anything else will not produce a risk that would exceed EPA's acceptable risk.

The question may be asked why are we so interested in using phosphogypsum. We do believe that leaving it in the stacks is a worse situation than using it. The road building economics are very attractive. The roads we built in Polk County, we saved $100,000 a mile by using phosphogypsum over traditional material. The actual soil use--using it for agriculture in Florida could have an even greater impact. All of the southeast is short on sulfur. Using our phosphogypsum, we would be able to increase the production and definitely affect what cattle raisers do in Florida.

One of the things we would like to continue at this point is using it in landfills. We have demonstrated in both pilot and in the bench scale tests that it would be possible to speed up the decomposition of the material in solid waste landfills. If we can do this we would be able to decrease the amount of landfills that would be needed by 50 percent.

We believe that all of these uses are practical, that the risks are acceptable and we would like to see something happen.

Mr. Putnam. Thank you very much, Mr. Lloyd.

[The prepared statement of Mr. Lloyd follows:]

[GRAPHIC] [TIFF OMITTED] T5739.003

[GRAPHIC] [TIFF OMITTED] T5739.004

[GRAPHIC] [TIFF OMITTED] T5739.005

[GRAPHIC] [TIFF OMITTED] T5739.006

[GRAPHIC] [TIFF OMITTED] T5739.007

[GRAPHIC] [TIFF OMITTED] T5739.008

Mr. Putnam. Our next witness is Dr. Malcolm Sumner. Dr. Sumner is an agricultural and environmental consultant. Currently he is Regents' professor emeritus at the University of Georgia. He graduated first in his class with a BS in agriculture and cum laude with his masters of science in Agriculture from the University of Natal in South Africa. Additionally, he has a doctorate of philosophy from the University of Oxford. He has edited five books, including the Handbook of Soil Science; authored and co-authored two books; 249 referred papers; 41 book chapters and over 300 publications. Dr. Sumner's specialties include soil contamination and pollution, beneficial reuse of anthropogenic, solid and liquid wastes in agriculture and gypsum as an ameliorant for subsoil limitation, among many other topics. He has extensive experience in international soil science and agronomic research, consulting and teaching. He has received numerous awards recognizing his scientific contributions, including an honorary doctor of science degree from the University of Natal in 1997.

Aside from the fact that you are a Bulldog, you are a very well qualified individual for this panel. Welcome, Dr. Sumner,

you are recognized.

Mr. Sumner. Thank you, Mr. Chairman. Today I am going to talk about the agricultural uses of phosphogypsum. This should be judged against the EPA rule which came up with a value of 2,700 pounds per acre every 2 years for 100 years. This comes down to 1,350 pounds of gypsum per acre per year. So that is the yardstick against which we should judge.

Now gypsum is used in many facets of agriculture, for sodic soils which do not occur in the southeast here, so I will not dwell on those at all. But as a calcium and sulphur source for crops, very important, as an ameliorant for the subsoil acidity and as a physical ameliorant.

I am going to deal specifically, Mr. Chairman, with the rates recommended by our Cooperative Extension Service, which is the imprimatur of the State and Federal Government. For peanuts, in terms of calcium requirements, gypsum is used to strengthen the cell walls of the peanuts to prevent them from getting diseased. The recommended rates vary from 250 to 1,720 pounds per acre every 2 to 3 years. So you are going to divide those numbers by two or three depending on the rotation. That gives you a maximum recommended value of about 600 pounds per acre and a most likely rate of between 125 and 430 with a minimum rate of between zero and 83.

For tomatoes, the gypsum is used to extend shelf life. The recommended rates are between 430 and 860 pounds per acre every 2 years. You have to divide those numbers by two, giving you a maximum rate of somewhere in the region of 430 pounds, most likely rates somewhere between 200 and 300 pounds and a minimum rate of between zero and 143 pounds.

As far as sulphur requirements of the crops are concerned, these are much lower than the calcium requirements, and the recommended values are between 54 and 161 pounds per acre, giving you a maximum of 161 and a minimum of zero.

As far as subsoil acidity amelioration is concerned, the recommended rates vary between 2.2 and 4.4 tons per acre every 10, that was in my report, but my work has continued and that can be now said to be every 15 years. So that gives the maximum rate at 800 pounds or for 15 years at 530 pounds per acre per year, and a minimum rate there would be zero.

To complete the picture, for sodic soils--which do not occur in this part of the world but occur in the western States--the recommended rates for gypsum would be between 7 and 35 tons per acre over the period of the reclamation which one can assume only once is 100 years, and that gives you a maximum rate of 700 pounds per acre per year and minimum rates of between zero and 200.

As far as soil crusting is concerned, the other physical ameliorant use, the recommended rate is between 0.5 and 1 ton per acre every 5 years giving you a maximum rate of 400 and a minimum rate of zero per year application.

For ameliorating subsoil hard pans there is no recommendation, but the rates that are being used are the regional 4.4 tons per acre every 10 years giving you a maximum again of 800 and a minimum of zero.

Now as far as the radiation hazard of the phosphogypsum is concerned, our experiments show that at the rate that we used, 4.45 tons per acre in one application, we found no significant increase in lead-214, bismuth-214 or radium-226 in the soil profile down to a depth of 3 feet over 5 years. There were no increases in radiation in the above-ground parts of the plants. In the sandy soil we found there was a light movement of radium-226 in a column study in the lab, but this level in the leachate was well below the drinking water standard.

So overall, from the rates I have shown you, the maximum rates that are actually likely to be applied in agriculture,

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this 1,350 pound per acre per year proposed by the EPA is too high. A more reasonable level in my view would be between 600 and 800 as the maximum, but the most likely rate, Mr. Chairman, would be between 100 and 400 pounds per acre per year.

The last point I would like to make, the basis of using concentration as the yardstick in banning the phosphate should be revised because I think cumulative load is much more important. Thank you, Mr. Chairman.

[The prepared statement of Mr. Sumner follows:]

[GRAPHIC] [TIFF OMITTED] T5739.046

[GRAPHIC] [TIFF OMITTED] T5739.047

[GRAPHIC] [TIFF OMITTED] T5739.048

[GRAPHIC] [TIFF OMITTED] T5739.049

[GRAPHIC] [TIFF OMITTED] T5739.050

[GRAPHIC] [TIFF OMITTED] T5739.051

[GRAPHIC] [TIFF OMITTED] T5739.052

Mr. Putnam. Thank you very much, Dr. Sumner.

Our next witness is Dr. Doug Chambers. Dr. Chambers is the executive vice president and director of radioactivity and risk studies at SENES Consultants Limited which he co-founded in 1980. He has been working in the area of environmental radioactivity and risk assessment for more than 30 years and has studied both radioactive and non-radioactive substances. Dr. Chambers has worked on projects across Canada, throughout the United States and abroad. He has participated on the United Nations Scientific Committee on the effect of atomic radiation since 1998 as a member of the Canadian delegation. Dr. Chambers is currently a consultant to UNSCEAR with responsibility for preparing the next UNSCEAR assessment of radon. He has supervised and carried out numerous studies of naturally occurring radioactive material in a wide variety of industries, including studies for the Florida Institute of Phosphate Research to examine alternative potential radiological risks arising from alternate uses of phosphogypsum in agriculture, road construction and daily cover at municipal landfills.

Welcome to the subcommittee, Dr. Chambers. You are recognized.

Mr. Chambers. Thank you very much.

As noted by Mr. Lloyd, the 1989 NESHAPS in effect converted phosphogypsum from a useful byproduct to a waste and the focus of the concern here was the radioactivity in the phosphogypsum, which is the same as the radioactivity in the phosphate rock and is naturally occurring.

In 1992 EPA did a reconsideration which allowed alternative uses with prior EPA approval. To my knowledge, I am not aware of any such uses having been approved to date. The EPA commented that the risk from indoor radon and direct gamma radiation were the issues of major concern at that time.

In their 1992 rule in deciding on the maximum acceptable level of radium-226 which they determined to be 10 picocuries per gram, the Environmental Protection Agency used a lifetime risk of 3 in 10,000. I will come back to that in a moment. It is interesting to note that in addition to the 1992 rule, the EPA has used the same lifetime risk of 3 in 10,000 to establish cleanup levels for unrestricted use in CERCLA Superfund sites which have been contaminated with radioactivity. This rule, I believe, specifically excludes the risk from radon in that

factor.

Another important consideration in looking at the EPA's 1992 rule is the rate of which phosphogypsum is assumed to be applied. I cannot compete with Dr. Sumner in that regard. I think I will basically compress my comment to the following: If you use a reasonable maximum application of perhaps 900 pounds then following no other changes in EPA's 1992 risk assessment you could then have unrestricted use of phosphogypsum containing up to 40 picocuries per gram by that simple change in the application rate to something that is more appropriate as opposed to an application rate of 2,700 pounds.

In their 1992 analysis, the EPA assumed a lifetime of 70 years of exposure, and yes, that is indeed possible but it is highly unlikely. In their Exposure Factors Handbook, a document prepared by EPA based on national data and surveys, EPA for other risk assessments recommends a duration of exposure of 30 years, which according to the EPA is the upper 95th percentile. In other words, only 5 people out of 100 might live longer in a single home than 30 years.

It is also interesting to note in their 1999 assessment of the risk from nonradioactive contaminants contained in agricultural fertilizers, the EPA used the average residency of a farmer of 17 to 18 years, also taken from their Exposure Factor Handbook. There is an inconsistency in this regard. I do not have time to go into the details but there is much more in my written presentation.

I would briefly like to comment on risk assessments we have done in support of FIPR's application for road construction, land use, agricultural application of phosphogypsum, daily soil cover for landfill. To comment that when you use distributions of parameters to take account of natural variability and uncertainty the numbers are very different. And we calculate using numbers that are generally traceable and would be consistent with many of EPA's risk assessments, upper risks that are below 1 in 10,000, well within the EPA's risk range from 1 to 3 in 10,000. I think this is very important. These numbers that we calculate would be for a person who lives in a home built on either a road that had been constructed with phosphogypsum or on land to which phosphogypsum had been applied for 100 years. We believe the maximum risk would be less than 1 in 10,000, much less even than the 3 in 10,000 risk limit that EPA has used. I believe it would be unfortunate to preclude beneficial and safe uses of phosphogypsum by unnecessarily conservative risk assessments.

Thank you very much.

[The prepared statement of Dr. Chambers follows:]

[GRAPHIC] [TIFF OMITTED] T5739.009

[GRAPHIC] [TIFF OMITTED] T5739.010

[GRAPHIC] [TIFF OMITTED] T5739.011

[GRAPHIC] [TIFF OMITTED] T5739.012

[GRAPHIC] [TIFF OMITTED] T5739.013

[GRAPHIC] [TIFF OMITTED] T5739.014

[GRAPHIC] [TIFF OMITTED] T5739.015

[GRAPHIC] [TIFF OMITTED] T5739.016

[GRAPHIC] [TIFF OMITTED] T5739.017

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[GRAPHIC] [TIFF OMITTED] T5739.018

[GRAPHIC] [TIFF OMITTED] T5739.019

[GRAPHIC] [TIFF OMITTED] T5739.020

[GRAPHIC] [TIFF OMITTED] T5739.021

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[GRAPHIC] [TIFF OMITTED] T5739.025

[GRAPHIC] [TIFF OMITTED] T5739.026

[GRAPHIC] [TIFF OMITTED] T5739.027

Mr. Putnam. Thank you very much, Dr. Chambers.

Our next witness is Dr. Chih-Shin Shieh. Dr. Shieh is an environmental consultant at the CS Environmental Solutions that he founded in Melbourne, FL. Dr. Shieh was research faculty and the director of the Research Center for Waste Utilization when he conducted the phosphogypsum studies at the Florida Institute of Technology. Dr. Shieh's areas of expertise include waste characterization, minimization and utilization. His academic training, research experiences and professional services have allowed him to become one of the few scientists in the Nation who are able to deal with problems concerning pollution that occur in both terrestrial and marine systems. Dr. Shieh has published more than 40 scientific papers and technical reports in the area of waste stabilization and utilization. He has graduated more than 14 MS and four PhD students under his tutelage. Welcome to the subcommittee, Dr. Shieh.

Dr. Shieh. About 10 years ago when I stood on the top of one of the 300-feet phosphogypsum stack piles, one idea that comes to my mind was what can we do about it. I mean, can we come up with a better approach to manage this material? And just like Mr. Chairman's opening statement, is phosphogypsum a waste or a resource? Now by definition, a waste is a substance that we do not want to use and has no usefulness at all. If the substance can be used for any beneficial purpose and in the meantime does not generate adverse effect to the environment then the material should not be considered as a waste.

So based on that concept we come up with an idea. We can apply phosphogypsum in municipal waste landfills. There is good evidence to suggest that the addition of phosphogypsum could enhance biodegradation of municipal waste in landfills, because during the early stage of waste decomposition in landfills the degradation process is essentially aerobic. That means it depends on the oxygen available so the microorganisms can carry out the process of biodegradation. However, very soon over time as oxygen is depleted the decomposition process becomes anaerobic. That means the bacteria used--you know, some oxygen compounds result dealing with free oxygen in the air. In an anaerobic process--again, that is in an oxygen depleted environment--bacteria depends on oxygen bound in the compound to carry out biodegradation. If there were limited oxygen bound compounds then the biodegradation process will be significantly minimized. So that is why it has been reported that buried bacteria--I am sorry, vegetables such as lettuce--a piece of lettuce was still in good shape after being buried at a site for more than 20 years, because the biodegradation was limited.

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Since phosphogypsum is enriched with sulphate it is reasonable to assume that sulphate using bacteria colonies present in landfills will use phosphogypsum as an energy source after oxygen is depleted. The sulphur enriched phosphogypsum can be used in anaerobic conditions such as landfills.

About 10 years ago, in 1996, we carried out a three-phase study. Phase I took about 2 years, from 1996 to 1998--I am sorry, 1994 to 1996. The phase II started from 1997 to 1999 and three questions were addressed. First, does this concept work? Is this only a hypothesis or is this practical issues? Secondary, we want to know under what conditions this concept could work. And third, we want to answer if this process would generate any adverse effect to the environment.

So in the phase I studies we concluded that yes, this concept is practical. Under experimental conditions phosphogypsum can actually be used by the bacteria and generation of a diverted level of hydrogen sulfate was not found. Also phase I study concluded that if we put one portion--one part of phosphogypsum with three parts of municipal waste together, the reaction would meet our purpose.

So following phase I, we carry out phase II right away. Similarly phase II is to kind of extend the reaction period and use a simulant of municipal solid waste, and we come up with similar conclusions that one portion of phosphogypsum can be used with municipal solid waste and can achieve more than 50 percent reduction in organic matters in 3 months.

So then immediately after the phase II study, we proposed to carry out a phase III field study. That was in 1999. That was about 5 years ago, and it is still pending EPA's approval. Through the field study we will come up with very conclusive findings to demonstrate that this approach is an environmentally sound approach and a lot of parameters will be monitored in the phase III study to further assure there is no adverse effect to the environment.

Thank you.

[The prepared statement of Dr. Shieh follows:]

[GRAPHIC] [TIFF OMITTED] T5739.028

[GRAPHIC] [TIFF OMITTED] T5739.029

[GRAPHIC] [TIFF OMITTED] T5739.030

[GRAPHIC] [TIFF OMITTED] T5739.031

[GRAPHIC] [TIFF OMITTED] T5739.032

[GRAPHIC] [TIFF OMITTED] T5739.033

[GRAPHIC] [TIFF OMITTED] T5739.034

Mr. Putnam. Thank you very much.

I want to thank all of our panel one witnesses. You know, for those who are trying to digest everything that these engineers and scientists have put before us, what I've heard is that you have through research identified essentially three key potential uses for phosphogypsum--road construction, soil amendment for agricultural purposes and the potential for cover fill on municipal solid waste landfills. And that there has been a great degree of inconsistency, almost a double standard or a rule unto itself promulgated by EPA that applies to phosphogypsum but does not apply to their risk models for other types of products that they are running risk assessment models on. So if we could, let us kind of start at 40,000 feet and work our way down.

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What--to any or all of you--do you believe that the risks associated with dispersing phosphogypsum either through landfill, road construction or agricultural purposes, do you believe that the risks associated with its dispersal, outweigh the risks of stacking it in a concentrated form in the types of mountains that we see? Which risk is greater, concentrating it or dispersing it? We will begin with Mr. Lloyd.

Mr. Lloyd. No, I definitely do not think that the risk of using it is as great as leaving it in the stacks. I think you are going to have some long term effects that you will have to deal with. My concern with using it is basically not very large. One thing that I would tell you is, if we built a road with it, I would have no argument about my children or my grandchildren or myself living alongside the road, and I would not have any concern about living in a house 100 years from now, which I will not get a chance to do, that had been fertilized with phosphogypsum. I think the work that Dr. Chambers has done demonstrates this very, very strongly in a scientific basis.

Mr. Putnam. Dr. Sumner.

Mr. Sumner. Mr. Chairman, I cannot speak for the risk of the stack because that is out in my backyard. I do not know much about that, but I can tell you pretty well categorically that if you use phosphogypsum at the recommended rates according to the Cooperative Extension Service, there is absolutely no risk because we were able to find no radiation residue as a result of applying phosphogypsum in all the agricultural applications that we have made. In fact, if one is concerned about the radon gas, in many parts--not so much in Florida, but in much of the Piedmont part of the Southeast, the radon emanating in basements is probably a bigger threat than anything you would ever get from phosphogypsum. So I think the risks are absolutely minimal when used correctly. Now, of course, if you use it incorrectly that is another matter, but that is off-label so to speak and one cannot address that in a hearing like this.

Mr. Putnam. Dr. Chambers.

Mr. Chambers. Thank you. I would like to make two comments. First of all, I agree with Mr. Lloyd that the use of phosphogypsum for agriculture, for roads, for daily cover on a landfill, and there are some other uses we did not have a chance to talk about today as well, would indeed in my opinion actually be smaller risks than the risk associated with leaving the phosphogypsum in the stack.

The referenced scenario here is building a home. So if you were in the future to lose control of the land--and that is a whole other issue--and build a home on a phosphogypsum stack the radium-226 concentration, which is really the issue we are talking about, would in fact be simply the radium-226 concentration in the phosphogypsum per se. For any of the uses we are talking about with appropriate land application with dilution in the daily cover, the actual final concentration of radium-226 would in fact be smaller than it was in the undiluted phosphogypsum, and indeed so small that it would be difficult to find within the natural variability of radium-226 which occurs in my backyard and your backyard and everybody's backyard. And indeed the radon flux that would arise from the incremental radium-226 because of the phosphogypsum would in my opinion be so small that it would not be detectable within the natural variation of radon that occurs in homes in Florida and indeed throughout the United States at the present time. Setting aside the absolute risk, which I personally believe to be extremely small, the incremental risks compared to radium and radon from natural background would be vanishingly small and in my opinion not measurable. Thank you.

Mr. Putnam. Dr. Shieh.

Mr. Shieh. If the use of phosphogypsum is under good monitoring, I do not think that kind of use will be worse than current practice.

One comment about the future of building on the site, the possibility in terms of risk assessment. For some reason that concept has been used everywhere in the whole country. When I was involved in Zinereta Ash project a similar question was always asked, how about 100 years later if my grandchildren build a house on the abandoned site with all kinds of waste material? We need to be honest and understood that today we already have very good systems, OK. One of the provision of service I am doing now is when the builder or the developer, they try to develop a site for new business, community or new residential community, they are required to do so-called phase I site assessment studies. And through that study any location--any property will be investigated for the history of the property. So practically and realistically that scenario will not happen even 100 years later unless the whole governmental system was destroyed for some reason, otherwise that is really not a scenario that would happen, that someone would build a house on the top of a waste pile. It is not going to happen. Again, we have very good system today already. So I truly believe if any good use of the material and under monitoring, then I support that idea.

Mr. Putnam. You know, the only way to deal with these issues is in a straight-forward science-based manner and you have certainly given us a foundation for a science-based approach to alternative uses of phosphogypsum. But, you know, radioactivity, that term certainly conjures up concerns, fear even among people. Help the subcommittee to understand the context of the radium-226 levels. How does it relate to other commonplace daily activities that people may be engaged in and whatever the background radiation of those may be, whether it is flying or smoking or the presence of radon in homes today? Help us put that number in context.

Mr. Chambers. Perhaps I will try. First of all, I would like to try and provide a small context on the risk range of 1 times 10 to the minus 4. As I mentioned--that is 1 in 10,000--as I mentioned earlier, the EPA has also used risk numbers as high as 3 times 10 to the minus 4 in rulemakings and therefore at least for that purpose, EPA, one would presume, considers that level of risk as safe. Well what is a risk of 1 in 10,000? That is a lifetime risk. So if you use EPA's notion of a lifetime of 70 or 75 years, in essence that works out to an annual risk of about one in a million. I am not going to tell you my exact age, but I am somewhere between 50 and 60 and it is pretty typical unfortunately that at my age natural causes of death in the average person, I would have a risk of about one in a million from just 1 hour of doing what I do every day. So assuming this hearing this morning takes 2 hours, my risk would be approximately two in a million just from just simply sitting in this room and enjoying this conversation. That's the kind of context we are looking at. It is a risk I suffer every hour or am exposed to every hour of the day at my age. It is unavoidable.

Radioactivity is unavoidable. All soils everywhere have naturally occurring radioactivity and in particular radium-226, which is the focus really of this discussion because it is a source of the radon that crops up in the open air and comes through our floors into our homes.

In any event, if you look at--it does not matter whether you look at EPA's risk assessments or ours, the incremental contributions of radium, even after 100 years of application, that I think this panel would consider exceptionally high

application rates, is still well within the range of natural radium-226 in soils. So you are not going to be changing that. And if you look at--GEOMET did a very detailed study of radium in soils and indoor radon in homes in this county and in many other counties in Florida. And if you look at the maximum incremental radon contribution it is less than a tenth of the average and less than a thirtieth of the upper number. It is a very small fraction, much less than the variation you would go from one home to the next because of the difference in life styles, slightly different age of construction. It is not a detectable phenomenon. I am a physicist, I like models, it is something I can predict. It is something EPA can predict, but I believe it is not something you could actually measure because it is there naturally in much higher and very variable quantities.

Finally I might add, the EPA has a 4 picocurie per liter standard at which they would like to have people initiate cleanup in the homes and what we are talking about, the maximum incremental contribution that I would predict would be more than 20 times smaller than that. The absolute maximum much less the average.

I hope that provides some context. Thank you.

Mr. Putnam. Does anyone else wish to add anything to that? Mr. Lloyd.

Mr. Lloyd. I always find it kind of comical that since you are in a granite office building in Washington, you probably have more radon than what most of the people in this room experience in a day.

Mr. Putnam. EPA has a nice big granite building, too, maybe that is what is going on there. [Laughter.]

The roads that were constructed in Polk County, there are homes along that road, Mr. Lloyd. Do you know how many homes are along that road?

Mr. Lloyd. May I ask a question?

Mr. Putnam. You may.

Mr. Lloyd. John, how many homes?

Voice. About 40.

Mr. Lloyd. About 40.

Mr. Putnam. Forty homes along the road that had phosphogypsum used as the road base. Does testing continue along that road?

Mr. Lloyd. Testing is continuing on it even until today.

Mr. Putnam. And you mentioned that the DOT testing indicated that roadbed has grown stronger over time, which is certainly a favorable thing for its durability as a roadbed, but what are the health effects that have been detected as part of that testing?

Mr. Lloyd. The road is kind of difficult to come up with the health effect for one reason. Everything we have shown is fairly normal. The land the road is built on is reclaimed land. The radiation over the land next to the road is higher than the radiation on the road. So the people that are living there are experiencing radiation levels that are higher than they would ever have if they built the house on top of the road.

Mr. Putnam. OK. What other leachates have been found in the monitoring of the roads already built in Polk County?

Mr. Lloyd. The only thing that we may have seen--and I will ask Dr. Burkee to correct me if I am wrong--is the sulphate increase at one well.

Mr. Putnam. You mentioned that NASA and the Department of Energy have expressed an interest in using phosphogypsum based glass in a ceramic material. Could you elaborate on that?

Mr. Lloyd. Well we have a proposal to make glass out of phosphogypsum. We have done all the research. We are trying to--the people that did the research are trying to put together

a system to start making glass. One of the techniques that has been studied would actually--in preparing the phosphogypsum for use, would enable you to produce hydrogen. In the course of our discussions--and this is still a preliminary study at this point, a paper study more than anything else. But in talking to both NASA and DOE, they are very interested in the fact that you might be able to produce hydrogen. NASA because they use it for launching space vessels and DOE because they would like to see us go this hydrogen-based economy that has been proposed that would reduce greenhouse gases. We are interested and we are working. That is all I know to say at the moment.

Mr. Putnam. All right, sir. Dr. Chambers.

Mr. Chambers. I have one further comment. I did not have the chance in my comments this morning to say anything about the glass. I would like to point out that when you make the glass you do not do anything obviously to change the gamma radiation, but, in fact, you trap the radon. The radon cannot escape. So in essence because it is like wall tiles--it is like a ceramic like material--the radon which has a half life of 3.8 days will decay within the glass like material and actually not be available to enter the rooms of living spaces or working spaces. So in actual fact, the radon risk in that case would be very much lower.

Mr. Putnam. Could you elaborate on the half life of 3.8 days? Was that what you said?

Mr. Chambers. Yes, I will. Radon-222 is a noble gas so it is able to diffuse through air and through soils, but it does have a radioactive half life. If you take 120 atoms of radon now in 3.82 days you will have approximately, plus or minus, 60 and in 7.6 days if my arithmetic is correct, you will have half of that again. So you will have 30. In another 3.8 days you will have 15. That is about as far as my mental math can carry me.

But in essence the radon that is produced within the matrix of a soil, within a matrix of PG, within a matrix of a cemented road can only survive because of its physical half life for a finite time and the average time is 3.8 days. Therefore, if something interferes with how easy it is to diffuse through the pore space well then it will decay and never actually enter the open air or the air of a building in which you might use tiles for a roof or a floor. So in actual fact, as I say, it does not do anything to change the gamma levels which is another kind of radioactivity. But certainly making it into a glass-like material hugely reduces the fraction of radon that can survive long enough to actually be released into room air. Thank you.

Mr. Putnam. Thank you.

The EPA risk model for phosphogypsum was a 70-year residency for occupants of a hypothetical house. When calculating the risk for phosphogypsum that is 18 hours a day, 7 days a week for 70 years. Does that assume an airtight house, air conditioning, no air conditioning, ventilation, windows open? How does that factor into that risk assessment?

Mr. Chambers. If I understand the EPA's risk analysis correctly, I do not think they actually considered any of that. I think they used--I stand to be corrected, but I believe they used a generic factor whereby they took the radium concentration in the soil that will be built up over time by application of this very high fertilizer rate, for example, and then use a factor--for every picocurie per gram of radium-226 in the soil you would find 1.25 picocuries per liter in the indoor air of the home. So it is a generic--it is a generic number.

Mr. Putnam. And what is a more reasonable risk analysis number to use other than the 70-year residency?

Mr. Chambers. I have some sympathy for EPA nationally, but

when you look at--for example, in Florida there is a huge amount of data that relates--from the GEOMET survey, for example, that relates specifically to soil concentrations of radium and the corresponding indoor radon levels. So one of the things that we did in our risk assessment for uses in Florida was to try and use as much Florida-specific data as possible. I think it is important where information exists to use data that is appropriate for the application and appropriate for the intended area of use.

Mr. Putnam. Mr. Lloyd, have you received approval from EPA to pursue NASA's request to utilize phosphogypsum in glass?

Mr. Lloyd. We have not really talked to EPA about the glass. That will be the next thing when we decide to go into a full scale plan. We have done all the benchwork, we have done all the pilot work. We would like to go into a demonstration sized plant and that is in the works. We will need to go to EPA at that time. Based on our past experience with them, it will take 3 or 4 years to get an answer.

Mr. Putnam. Do you have any permit requests pending with them now?

Mr. Lloyd. We have one with them for the landfill that Dr. Shieh mentioned. Down in Brevard County they have agreed to let Dr. Shieh build a test cell that would be large enough to demonstrate to landfill operators the effectiveness of this technique. We asked 2 years ago, plus or minus, to get approval to do that. We have had--the problem we experience with most of these things is EPA said in 1992 that they would define the method to get an exemption to the rule. They have never done anything. We have tried to put things together, working particularly with Dr. Chambers for requests that would meet all of the requirements. Our biggest problem is we turn it in and in about 4 months, 6 months or 8 months later we get something that says you need to add this. So we add that, and in another 4, 6 or 8 months we get another request that says you need to add this. So getting anything through EPA in terms of an exemption to the rule is not the simplest thing that anybody ever did. The only thing that we have that would stand up today is, EPA has said that if we wanted to build a road, if we would get a deed restriction on the road so that you could never build a house on it, that they would have no objection to building the road. But even when we have worked with getting an exemption request for a given road, even with a deed restriction, we have to have an exemption request. It has been a long-term, frustrating affair.

Mr. Putnam. Dr. Sumner, you went into great technical detail on the calculations that EPA used particularly for the agricultural uses. Could you take some time to elaborate on the calculations they made versus the calculations that you believe that they should have made using realistic assumptions for the soil types and the crops that are being tested?

Mr. Sumner. Well they came up with this value that was 2,700 pounds per acre every 2 years. That is the standard that they set the rule on. Now, I do not know the exact calculations that they went through establishing the rule. What I am saying is that the uses of gypsum that are recommended by the Cooperative Extension Service are all much below that level. So that should--the actual uses that are recommended in the agricultural industry are the rates that should be used in the calculation, not the value they used. That is my point.

Mr. Putnam. Are the calculations that they used available?

Mr. Sumner. Yes, I think so. Well, I do not know if they are available. I started at the point of 2,700. That is what I know. I do not know about their calculations.

Mr. Putnam. Are the working papers that are used by the EPA, are they available to the public through our traditional

open records laws?

Mr. Lloyd. The working papers for the 2,700 pounds are available in the BID documents for the 1989 rule. What they did was take California's applications for sodic soil, which is, as Dr. Sumner has mentioned, are significantly higher than you would use for fertilization. They took those and averaged them with numbers that were used for fertilization from Georgia and Florida. They did a couple of things wrong when they did this. No. 1, they were not agronomists obviously. They did not look at what Dr. Sumner has mentioned about peanuts in which you apply phosphogypsum 1 year but you do not plant peanuts again for another 2 years. You use a 3-year crop rotation. If you do not do this, you get nematodes that destroy the quantity of peanuts and you get a fungus that will destroy the quality. So they took these two totally dissimilar techniques and used them to average to come up with a 1,350 pound per year average. We should really be dealing, as Dr. Sumner says, probably no more than 400 or 500 pounds per acre. We should not be comparing, as I say, the soil treatment with fertilization. This is like taking apples and oranges and saying they are both the same because they are fruit.

Mr. Putnam. You have made that point that the California numbers are irrelevant to the needs of the Southeast. Could you explain what a sodic soil is and why it is a different animal than the Southeast?

Mr. Sumner. Mr. Chairman, I think I will do that.

Mr. Lloyd. He can do a better job than I can.

Mr. Putnam. Go right ahead.

Mr. Sumner. Sodic soil, Mr. Chairman, is a soil that is impacted negatively by the presence of sodium irons. The sodium irons in the soil cause the physical properties of the soil--in other words, the ability of the soil to accept water at the surface and transmit water through the profile--to be very negatively impacted. So in sodic soil the transport of water from rainfall to some groundwater point is impacted very negatively. It is very slow and they are very difficult soils to work on. The phosphate--well phosphogypsum or any gypsum--generic gypsum is used in the reclamation of these soils and supplied at--relative to what we use in the Southeast here, relatively high rates, in order to exchange the sodium from the exchange complex of the soil and replace it with calcium which improves the physical condition of the soil. So that is a reclamation technique, and you would only do that once. So the rates that they use, sort of 35 tons maximum, would be for a one time application to reclaim the profile so you can bring it back into agriculture. So you should divide that by 100, in my view, by the standards that the EPA has used to assess the annual rate, because you only apply that once in the whole lifetime of the soil. Once you reclaim the soil, it will stay reclaimed provided it would not be inundated by the sea or some other negative introduction of sodium into the soil. So once you reclaim it it is reclaimed. So that is the crux. And, of course, it is not relevant here in the Southeast at all. We do not have any sodic soils that are in agriculture in the Southeast at all.

Mr. Putnam. Now in north Florida the phosphogypsum byproduct of the mining up there is allowed to be used as a soil amendment and it is used predominately by peanut growers. Do you believe that the differences in the north Florida phosphogypsum and the central Florida phosphogypsum are significant enough to allow the use of one and ban the use of the other?

Mr. Sumner. Do I think that?

Mr. Putnam. I will begin with you.

Mr. Sumner. Absolutely no. I mean, as far as I am

concerned, at the rate you would use them as an ameliorant for peanuts, I do not think you would ever be able to find any difference in the peanuts or the soil. I mean, it is far lower than the rates--we actually tested the radiation, it was applied at rates that were of the order of three and four times the rate that would be cumulatively applied to peanuts.

Mr. Putnam. Mr. Lloyd.

Mr. Lloyd. I do not think you would have any problem. EPA based their ruling on the fact that north Florida has 10 picocuries per gram of radium and central Florida has an average of 26, and that is where their differences came from. But I am like Dr. Sumner, I cannot see where you would ever have enough phosphogypsum used in agriculture for fertilization that it would ever cause a problem. We did have some work that was done by Dr. Jack Grexicle with the University of Florida using it on forage. As I have mentioned, in Florida, if we could do what Jack thinks we could, we could improve the quality of the grass to the point that we could make a very definite positive economic effect for the Florida farmer, because a cow uses grass that has the proper level of sulphur more efficiently than it does some other grass. You have demonstrated in parts of the world 20 percent weight gains just because of having proper sulphur fertilization. Jack is here today. If you all would like to have him address you, he can give you all the details.

Mr. Putnam. Dr. Chambers.

Mr. Chambers. Thank you, very much. It is difficult to add to what my colleagues have said, but I would like to make one additional comment. As Mr. Lloyd indicated there is considerable detail about the EPA's risk assessment in the 1992 BID, including the EPA's own analysis of the effects of a biennial, every 2 years, application rate at 900 pounds per acre for 100 years. Without any other changes, even leaving the 70 years, and without any other changes to the risk assessment the EPA themselves indicate the lifetime risk from the application of 900 pounds every 2 years is less than 1 in 10,000, well within their risk range. So even if you--even if you doubled that, that would still be well within the range of 3 in 10,000. So I think simply without any other changes, even by EPA's own risk assessment, with the appropriate application rates there should be no restriction in my opinion at least on the use of phosphogypsum as an agricultural installment.

Mr. Putnam. Dr. Shieh, do you wish to add anything?

Mr. Shieh. No. I did not study on this subject, so I do not want to make comments.

Mr. Putnam. The phosphogypsum from north Florida is allowed by law to be used for agricultural purposes and the phosphogypsum down here is not, and it is not allowed to be used for a roadbed with the exception of the test roads that were built. Now this being Florida, do you not believe, Mr. Lloyd, that the likelihood of building homes on top of previous agricultural land is greater than the likelihood of building a home on a road bed?

Mr. Lloyd. Well, I have always had a problem in understanding why anybody would build a house on a roadbed. [Laughter.]

Particularly in Florida. I do not know how to explain the logic. That is all I am going to say. I would doubt--I just do not know where this ever happens, but I doubt that it is going to happen in Florida.

Mr. Putnam. Well, I do not want to ask our scientists who are very precise to speculate outside their field, but I think that the facts would show that more homes are built in Florida every year on former agricultural acreage than on former road beds.

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Dr. Shieh, you suggest that the bacteria would use the sulphate enriched phosphogypsum after oxygen is depleted and delay anaerobic decomposition. Does that have any beneficial effects on methane reduction in landfill?

Mr. Shieh. Yes. When I say that is typical in an ordinary landfill, carbon dioxide would be generated first when there was oxygen available, so that would be the byproduct of organic decomposition, is generation of carbon dioxide. And over time, when the oxygen has been depleted, the methane begins to degenerate and the carbon dioxide begins to convert to methane. So it is like a curve, from there, to rise and decrease over time and methane from left to right will increase over time. So there is intersection at a certain point. What we discovered is that the intersection between the two extends beyond the time. That is an indication that the production of carbon dioxide has extended, prolonged, as many more organics have been decomposed. And in the meantime, the generation of methane was delayed because as the more organics decomposed slows up the actions.

So that is what I meant in the summary, that by introducing additional available sulfate in phosphogypsum, that would extend and provide opportunity to have more organic matter decomposed and that further would reduce the volume of the waste accumulated at a landfill. And that is why we say we might be able to extend the lifetime of the landfill.

Mr. Putnam. So increasing the efficiency of the decomposition. Has your research given you any indication of how many more years of service a municipality or local government may get out of that landfill if they were able to use phosphogypsum as cover?

Mr. Shieh. Just based on the laboratory results, for example, if we compare the experimental reactor and the control reactor, in 3 months, we actually see more than 50 percent of organic matter has been decomposed on the experiment with phosphogypsum. So we say 50 percent more of the organic matter will be decomposed from the landfill. So we can say that is two times that the time could be extended. So assuming the site, the ordinary landfill, they say is 25 years, so we might be proposing an assumption could extend to 50 years of time. That is one simple assumption. Of course, as I say, if we were able to carry out a phase III field study, then we would be able to come up with more conclusive comments.

Mr. Putnam. And you have a request pending before EPA to your phase III study?

Mr. Shieh. Yes.

Mr. Putnam. And when did you submit that request?

Mr. Shieh. Immediately after completion of phase II, we submit to FIPR and FIPR went through the typical reviewing process, tech committee and the board of directors. They reviewed it and they actually approved the funding but because of the issue on the radioactivity, we have to wait for EPA to make a final green light. That was in either 1999 or 2000, about 4 years ago.

Mr. Putnam. So you have been waiting 4 years for an answer to your request for your phase III.

Mr. Shieh. Yes.

Mr. Putnam. And were there adverse results in phase I or phase II that might have led EPA to delay their decision?

Mr. Shieh. I do not think so. Throughout the phase I and phase II studies, except the issue on radioactivity, which we did not address because that was not a task of the study. On the other hand, we looked at the possible production of hydrogen sulfite, because when we introduce additional sulfur, theoretically we will consider there is going to be more hydrogen sulfite produced at the site, and theoretically that

is possible.

Another possible adverse effect would be the generation of ammonia. Ammonia at the site would prohibit microbiological process. And our study showed that the production of ammonia did not actually stop the microbiological process and the generation of H2S, hydrogen sulfite, was really not on a register label comparing the typical landfill site. And the reason we investigate and the reason could be because of formation of metal sulfite. During the formation of hydrogen sulfite, the sulfur compound could create ways to dissolve metal in the leachate and form the metal sulfite. Under that scenario, the hydrogen sulfite would not be generated.

So we believe throughout the phase I and phase II studies, there is no adverse effect that could make the EPA slow down the process, and personally, I have no idea why they cannot make a decision as quick as possible.

Mr. Putnam. Thank you, we'll have the opportunity to ask that this afternoon.

Dr. Chambers, you have gone into some detail about the 1 in 10,000 versus 3 in 10,000 standard. Are there other examples that you are aware of where they employ a 1 in 10,000 standard instead of their typical 3 in 10,000?

Mr. Chambers. I believe I pointed out another example in my written testimony, which relates to the cleanup of a radioactive contaminated site from the fuel cycle. EPA I believe has a 15 millirem per year dose limit and the NRC, for the same situation, has a 25 millirem, and this has been much discussed. EPA equates a 15 millirem dose to a risk of 3 in 10,000, but it is also very clear that 15 millirems does not include the dose from radon. So in actual fact, if you added radon in, the equivalent risk level would be much higher.

I do believe that in that context, EPA would require a demonstration that you did not exceed their 4 picocurie per liter limit in addition to the 15 millirem.

Mr. Putnam. The 95th percentile application rate--and this is a followup to what we just discussed--is the 1 in 10,000 the 95th percentile, or is 3 in 10,000 the 95th percentile?

Mr. Chambers. The 3 in 10,000 was the upper 95th percentile, which was the 2,700 pounds we referred to previously. As I mentioned though, the EPA's own analysis, using all their parameters in the 1992 BID concluded that an application rate of 900 pounds would produce a risk less than 1 in 10,000. So even if you doubled that to 1,800 pounds a year, that would certainly be less than 2 in 10,000, still within the EPA's risk range of 3 in 10,000.

So I think with the application rates that Dr. Sumner has indicated, that the EPA's own 1992 analysis would demonstrate, even with the conservative assumptions that they have made, that risk to someone building a home on land to which you applied 900 pounds or even twice that, for 100 years, would be well within their acceptable risk range.

Mr. Putnam. We have focused mostly on the road bed, the landfill and the agricultural uses with the additional potential for the glass use. Dr. Shieh, you have done some work on the marine side of things. Are there potentials in that arena as well?

Mr. Shieh. In the marine environment, we actually had some idea in terms of using the material for artificial reef in the ocean. Our organization did not make this proposal. Louisiana State University with a similar group, they actually proposed to do that. Maybe Mr. Lloyd can make a further comment on that.

But yes, based on our previous studies and experience, we agree this material can be used for marine purpose, because the material is good for stabilization, can turn into a solid substance without any question at all. So if the radioactivity

issue can be resolved, I do see it as a good application in the marine environment.

Mr. Putnam. Thank you. Mr. Lloyd, did you want to add anything to that potential use?

Mr. Lloyd. Louisiana State has done a great deal of research on using it in marine applications. They originally proposed using it for oyster conch, which is the solid material on which the young oyster attaches and grows from that point. It used to be you took all the oyster shells and returned them to the ocean and the young oysters could grow on the old oyster shells, but they have become too valuable to be put in the ocean. So now, they do import into Louisiana, granite out of Mexico. One of the problems in much of the Gulf is you put down this material and it is on top of the soil and over a period of time, it sinks down into the soil. So you no longer have a site for oysters.

In addition, they want to use material of this nature to stop the erosion of some of the shores along the Gulf. There is a great deal of erosion into the marshes in fact all along the Gulf in Louisiana.

And a third application that they are working on is for artificial reefs. They have developed formulas that would be economical and compete with material that would come out of Mexico. They have looked at the radionuclide situation to see what would likely happen if they had oysters growing or any other marine creatures growing on this material and they have determined that there is not a significant problem with any of the materials in phosphogypsum going into the food chain.

But they are quite enthused, and in fact, I have a proposal on my desk for some additional work right now from Louisiana State.

Mr. Putnam. That is an interesting segue into what other States are doing. Phosphate is not only mined in the United States either. What are other nations doing with phosphogypsum, what are the permitted uses in some of the other areas that also have phosphate mining? Dr. Sumner, perhaps you could speak to that?

Mr. Sumner. Well, being a native South African, I know the situation in South Africa. The phosphogypsum that is made there is not radioactive, the source of phosphate is a different source and does not contain anywhere near the level of radioactivity that the Florida source does. And the gypsum is freely available and in fact, the excess until recently--they might not have stopped yet, but they are about to stop--was pumped out to sea. So there appears to be no environmental hazards associated with that at all, because it does not contain any radioactivity.

And may I add one----

Mr. Putnam. You may.

Mr. Sumner [continuing]. New potential use, Mr. Chairman. Research has been carried out at the University of Georgia and is still underway, but in a very minor pilot study, we have found that application of gypsum, and it was not phosphogypsum, but generic gypsum, on the top of poultry litter in poultry houses, we can look forward to the possibility that when that litter is applied on land, that the application of gypsum will reduce the level of water soluble phosphorus which is a serious concern for the contamination of surface waters. We have only done this in the lab, pilot study, still going to be extended to the field, but that is another potential source that will be considerable in magnitude throughout the country because of the chicken industry being quite ubiquitous.

Mr. Putnam. Thank you. Dr. Chambers, would you like to speak to the international nature?

Mr. Chambers. Yes, I would. First of all, I would like to

say that the EPA is well-regarded, as it should be, nationally and internationally, and quite often--I was in Brazil last year and Brazilians basically look to EPA for what can be done with phosphogypsum in application there, again, for road construction. So the EPA's determinations are very important and they extend, not just in Florida and throughout the United States, but they have worldwide implications. And that was a road application I was involved in.

In Canada, at the present time, there are a variety of uses being looked at, one of which--and I am not an agronomist, so I apologize here, but I know that a company north of Edmonton is working with feedlots, cattle feedlot users, and the phosphogypsum is being mixed on an experimental basis to reduce odors. And it apparently is extremely successful. That could be a potentially important use.

There have been experimental studies done on using phosphogypsum to reclaim in northern Alberta something called the Tarsands, which is a large mining operation, there has been experimental work with regard to using phosphogypsum to help reclaim Tarsands, a very good, positive, positive thing, and it worked very well on the experimental test.

So there is work underway. I cannot speak to the work that is carrying on worldwide, but there do appear to be a number of potentially beneficial uses, which have to be carefully thought out to make sure we are not putting anyone at risk, as I said before.

Mr. Putnam. Mr. Lloyd, prior to 1989, before EPA redefined a commercial product as a waste product that was therefore eligible for regulation, what were the primary uses of the phosphogypsum byproduct, and was it ever used in the construction of a building, for example?

Mr. Lloyd. Could I answer that construction thing first? Not in this country, but overseas at that same time, you were doing it in Japan with phosphogypsum for building products, wallboard and other structural members; in France, in Belgium; in Germany, at times they have used this for making structural members as well as wallboard. There was no real problem with that.

The biggest uses in U.S. history were agriculture. In California, you had a phosphoric acid plant, there is no gypsum stack. The phosphogypsum was used literally as it was manufactured. In the middle of the United States, you have some phosphogypsum stacks, most of those, there was some gypsum used for agriculture. At the time of the EPA ban, the only commercial application on roads was in Texas and at that time Mobil was actually building roads using phosphogypsum. We were still experimenting and going in a different direction than what they did. They had a different technique than what we were proposing to use.

There have been roads built all over Polk County where the mining companies were concerned, that they used phosphogypsum. There are untold number of parking lots at churches and at places like that, that were built with phosphogypsum because somebody at church worked for the phosphate industry, they could get the phosphogypsum free. You did have one company around here, one paving company, that worked with phosphogypsum all the time on this type of job.

That was about the uses of it.

Phosphogypsum had been used in other parts of the world, not in this country, to recover sulfur to recycle it to make additional sulfuric acid, particularly in South Africa.

But those are about the only uses I know of at that time.

Mr. Putnam. Is there a potential for use on unpaved roads, as far as strength and durability and the amount that is spent by local governments to maintain clay roads, unpaved roads in

rural parts, is phosphogypsum suitable for that purpose, assuming it were permitted?

Mr. Lloyd. Structurally, yes. This is one of the things that we got into in north Florida with Columbia County. The road that was built up there is an asphalt paved road with a phosphogypsum base. One of the things they wanted to do was to go into all of their dirt, unpaved roads, and take and mix phosphogypsum into the soil and then compact it. The work we have done with Dr. Chang indicated this road would stand up an awful lot better than what the untreated road would. But that never went beyond that point.

When you do this, you will have to face the possibility of some leachate of calcium and sulfur because gypsum is very slightly soluble. We have not done any tests to be able to tell you what that would amount to.

Mr. Putnam. And do you know what the industry spends today managing the existing phosphogypsum stacks?

Mr. Lloyd. I would not even want to guess.

Mr. Putnam. Does anyone else have a comment on the environmental or economic impact of managing the stacks?

[No response.]

Mr. Putnam. Well, with that, I would like to ask each of our first panel of witnesses to make any closing comments that you wish to make, whatever issues we were unable to get to or whatever you wish could come out of this. This has been a process, very long in the making. I can remember trying to work through this issue in the legislature. Growing up in this area, watching these mountains come up, it certainly is an important issue I think for us to resolve for the environmental and economic health of central Florida. All of you have devoted your professional lives to it, so at this time, it is an open mic, beginning with Dr. Shieh and letting Mr. Lloyd have the last word for our first hearing. Dr. Shieh.

Mr. Shieh. OK. Well, as I said earlier, the result of the study has supported to concept of use of phosphogypsum in landfill applications and if we were able to carry out the field study, by today we should have some conclusive findings available to interested parties. If there were any adverse effects that needed to be addressed, we would be able to identify. So my true belief is if we have something on the way and be able to provide solutions to an existing problem, then I think we should go ahead and do it.

I want to emphasize that this approach will not solve overall our phosphogypsum stack problem at all, but it will provide a solution to help minimize the existing problem. So we are still just waiting and waiting without any solution. I think we should go ahead and make a decision to do it. Thank you.

Mr. Putnam. Thank you, Dr. Shieh. Dr. Chambers.

Mr. Chambers. Thank you very much. I will be brief, I think I have said most of what I want to say.

I would just like to reiterate from my examination of EPA's calculations and my own calculations that I believe the doses and the risks to even the most exposed person are small on an absolute basis and very small by comparison to the natural variation in dose from background radiation. And truly in that context, of very little concern.

I would fully support Dr. Shieh and I would like to see some of these tests at least licensed so we can actually get and confirm one model or the other. And I really do not understand the lengthy process in licensing, and in my opinion, it would be unfortunate if the theoretical concerns over radiological risks were to prevent uses of phosphogypsum that would be of benefit to the people of the State of Florida and indeed the country. Thank you.

Mr. Putnam. Thank you. Dr. Sumner.

Mr. Sumner. Mr. Chairman, in summarizing, I would like to first of all draw the committee's attention to another use of phosphogypsum. Currently I hold a patent which was based on wallboard for making kitty litter out of gypsum. It is self-clumping, odorless kitty litter. It is doing very well in the market based on recycled wallboard. But if we were to use phosphogypsum, it would be even better than recycled wallboard. So that is another potential use.

I would like to just finally say that the maximum rate in agriculture should be figured into the risk assessment calculations as between 600 and 800 pounds of phosphogypsum per acre per year. That would be the maximum rate that it could be used in agriculture.

Thank you, Mr. Chairman.

Mr. Putnam. Thank you. Mr. Lloyd.

Mr. Lloyd. I guess I always find it interesting when you re-invent the wheel. Dr. Sumner has said something about using phosphogypsum with chickens, with the waste from chickens. It has got to be at least 10 years ago that I told the DEP in Florida that was one of the ways to stop the odors from a chicken waste. If you will go all the way back into the 1900's, you will find the same sort of thing was practiced, both on dairy farms and other places, except they used what was then called normal super phosphate. But all of the gypsum, when you made normal super phosphate, ended up in the normal super phosphate. The gypsum was what knocked down the odors, what stopped the phosphorus leaching, what did all of the other things.

So we are re-inventing something that we should have known a long, long time ago.

I do think the landfill is one thing that ought to be put on a priority track. This is something that virtually every time you see somebody trying to build a landfill, everybody starts hollering and shouting do not build it near me. So one of the things that would be very beneficial, also very cost-effective, would be to build landfills and use phosphogypsum.

The Institute looks at things from so-called applied research point of view. One of the things in the area of phosphogypsum that we look at all the time is the economic impact. So when we start recommending one of these things, we are not only recommending it because we think it is environmentally sound, we know it is economically practical, and that it will contribute to the Florida economy. So this is one of the reasons we support all of the things we have done.

One thing I would mention, and I am sure that Dr. Chambers will second me on this, every time we have been able to sit down with EPA in a full scale scientific discussion, we have ended up making some progress. But that is again--next to getting an exemption application, that is one of the hardest things to do that you have ever tried to do. We have succeeded twice in the last 20 years. So if there would be some way that we could do this and let some of the things that Dr. Sumner has seen, let some of the things that Dr. Chambers has seen be presented to these people, we could probably make some progress.

I think for the opportunity.

Mr. Putnam. I want to thank all of you before we adjourn this first hearing. I want to tell you how much we appreciate the expert testimony that you have given this subcommittee panel. It strongly reinforces the premise that utilizing phosphogypsum can be safe and less costly to taxpayers and as well as being environmentally sustainable. I appreciate your willingness to be here, some of you have traveled a great distance to share your knowledge and experience and thoughts

and in some cases frustrations, and I would like to invite you to participate in the second hearing as well. So for those of you whose schedules allow, I would like for you to remain and participate in that hearing also.

In the event that there may be additional questions that we did not have time for today or did not get to, the record will remain open for 2 weeks for submitted questions and answers. And with that, we will stand adjourned for 15 minutes and reconvene hearing two at 11:15. Thank you.

[Whereupon, at 11:03 a.m., the subcommittee was adjourned.]

PHOSPHOGYPSUM: SHOULD WE JUST LET IT GO TO WASTE: PART 2

MONDAY, MARCH 15, 2004

House of Representatives,
Subcommittee on Technology, Information Policy,
Intergovernmental Relations and the Census,
Committee on Government Reform,
Bartow, FL.

The subcommittee met, pursuant to notice, at 11:30 a.m., in the West Wing, Southwest Florida Water Management District Headquarters, 170 Century Drive, Bartow, FL, Hon. Adam Putnam (chairman of the subcommittee) presiding.

Present: Representative Putnam.

Staff present: Bob Dix, staff director; John Hambel, senior counsel; Ursula Wojciechowski, professional staff member; Juliana French, clerk; and Matthew Joyner, district director.

Mr. Putnam. The Subcommittee on Technology, Information Policy, Intergovernmental Relations and the Census will come to order. This is officially the subcommittee's second hearing on phosphogypsum entitled, ``Phosphogypsum: Should We Just Let It Go To Waste?''

In 1989, the U.S. Environmental Protection Agency promulgated a rule determining that the commercial product of phosphogypsum was waste product and banned its use for any purpose whatsoever.

Three years later, the EPA modified the rule to allow the use of phosphogypsum from north Florida for agricultural purposes.

Since then, only one other rule has been promulgated. In 1999, EPA raised the limit on the quantity of phosphogypsum that may be used for indoor research and development from 700 pounds to 7,000 pounds and clarified sampling procedures for phosphogypsum removed from stacks for other purposes. This was a step in the right direction.

Testimony provided for our first hearing, which we just concluded, suggests that the use of phosphogypsum can be favorable to farmers, cattlemen and taxpayers, particularly local governments, as a landfill cover, when used as a soil amendment, road base and again, landfill additive. Additionally, concern was expressed that the long-term adverse environmental effects of leaving phosphogypsum in stacks greatly exceeds any risks associated with its use for any purposes researched.

A number of other issues came forward that we hope to explore in this second hearing, including the delays in permitting for additional research and the inability to communicate effectively with the policymakers.

I would like to ask unanimous consent of the other subcommittee members to reseat the witnesses from our first

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hearing, so that we may benefit from a combined panel of expertise. Without objection, so ordered.

And without delay, I welcome our witnesses and look forward to your testimony.

As is the custom with the Government Reform Committee, all of our witnesses are sworn in. For those witnesses who were sworn in for the first panel, I would ask that you be sworn in again since this is technically a new hearing. And again, for any of our witnesses, if you have someone with you who will provide supporting testimony, slipping you notes, whispering in your ear, providing additional information for the benefit of the subcommittee, we would ask that they rise and be sworn as well.

So with that, please rise and raise your right hands.

[Witnesses sworn.]

Mr. Putnam. I note for the record that all of the witnesses responded in the affirmative.

Our first witness is Ms. Elizabeth A. Cotsworth, who is currently the Office Director of the Environmental Protection Agency's Office of Radiation and Indoor Air. She provides national direction for protecting people and the environment from harmful and avoidable exposure to radiation as well as protective measures and guidance for indoor air environments.

Prior to joining the ORIA, Ms. Cotsworth was the Office Director of the Office of Solid Waste from 1997 to 2002, after holding a series of positions managing national hazardous and solid waste programs.

She entered the EPA as a management intern in 1973, she holds a B.A. from Chatham College in History and an M.A. from the University of Virginia in Government and Foreign Affairs.

Welcome to the subcommittee. You are recognized.

STATEMENTS OF ELIZABETH COTSWORTH, DIRECTOR, OFFICE OF RADIATION AND INDOOR AIR, OFFICE OF AIR AND RADIATION, U.S. ENVIRONMENTAL PROTECTION AGENCY; HARLAN KEATON, ENVIRONMENTAL ADMINISTRATOR, BUREAU OF RADIATION CONTROL, FLORIDA DEPARTMENT OF HEALTH; AND DICK ECKENROD, EXECUTIVE DIRECTOR, TAMPA BAY ESTUARY

Ms. Cotsworth. Thank you, Mr. Chairman, for the invitation to appear here today. I will comment on the approach that the Environmental Protection Agency has implemented over the last 15 years to address the issue of protection of human health and the environment with regard to phosphogypsum.

EPA has specifically regulated phosphogypsum since 1989 with a national emissions standard for hazardous air pollutants called NESHAPS, authorized under Section 112 of the Clean Air Act. Radionuclides are listed there as a hazardous air pollutant. Radionuclides are a known cause of cancer and genetic damage. It is the processing of raw phosphate ore that specifically concentrates radionuclides into the phosphogypsum. Phosphogypsum contains naturally occurring radiation, as well as its decay products such as radium-226 and radon. Due to its health risk, its radon gas emissions in particular are the target of our NESHAPS regulation.

We strive to provide maximum feasible protection against risks to health from hazardous air pollutants, including radionuclides. We do so by trying to limit exposures such that an individual's lifetime excess cancer risk level is really no more than 1 in 10,000.

In our 1989 regulation, EPA specified stacks as the safest for phosphogypsum management. It is the use of stacks that provide appropriate risk protection with an ample margin of safety, as is required by the Clean Air Act.

Originally, there were no provisions for allowing

alternatives of the material, but petitioners approached us afterwards for reconsideration. We determined, considering all of the information available on potential exposures and the associated risk, that certain uses may be considered acceptable as long as those uses are restricted to limit the estimated lifetime risk to approximately 1 in 10,000.

We now allow three types of activities using phosphogypsum.

First, outdoor agricultural uses. For example, as a conditioner of soils with high quantities of salt or low concentrations of calcium or other nutrients, as long as the average radium-226 concentration is less than 10 picocuries per gram. For example, peanut farmers in Georgia apply phosphogypsum to their fields to strengthen peanut shells. Also, when several counties in North Carolina recently found farmland soils to have high salinity, in part because of Hurricane Isabel.

Second, indoor research and development activities using up to 7,000 pounds of phosphogypsum; for example, to study the production of road base and building materials.

And third, other alternative uses that are approved by EPA on a case-by-case basis.

Some activities do not meet the criteria for ensuring safety and health protection on a national basis. For example, we found that a generic national exemption for road building material could not meet the risk criteria. This is because of radium-bearing dusts, which are dispersed as the road surface degrades and radon emissions from the road itself. In addition, when road material is eventually removed, disposed or abandoned, additional exposures can occur.

As we review and consider the safety of new potential phosphogypsum uses, we work in partnership with our colleagues in State government, such as the Florida Department of Environmental Protection. In addition to potential exposure, our review carefully considers impacts on State legal authority and interests such as groundwater protection from any alternative use.

We have received several petitions requesting EPA approval of alternative uses for phosphogypsum. We are currently reviewing a petition for its use as a landfill cover at a municipal solid waste landfill in Brevard County, FL. We hope to have a response on the completeness of this application in the next month to 6 weeks. We are also simultaneously in the process of developing much needed guidance to further and clearly explain the criteria discussed in our regulations, specifically providing our sense of what information is required for a complete application that can then be evaluated for its support of a publicly and scientifically defensible decision.

We stress the importance of addressing radiation risk and giving confidence perhaps through monitoring, that other constituents in the waste, for example heavy metals, do not pose additional environmental concerns. Additionally, we seek to identify the benefits clearly associated with the alternative use and consistent with the principles of radiation protection, assure that potential exposures are justified and legitimate.

Managing phosphogypsum in stacks consistent with existing regulations is the best current management practice for most phosphogypsum. But we continue to be open to consideration of other beneficial and protected uses and remain supportive of research. Nevertheless, petitions submitted to the agency for such uses must clearly and fully demonstrate that the alternative use will be at least as protective as keeping the material in those stacks.

This concludes my prepared statement. I will be happy to

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answer any questions. Thank you.

[The prepared statement of Ms. Cotsworth follows:]

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[GRAPHIC] [TIFF OMITTED] T5739.037

[GRAPHIC] [TIFF OMITTED] T5739.038

Mr. Putnam. Thank you very much, Ms. Cotsworth.

Our second witness for this hearing is Mr. Harlan Keaton. Mr. Keaton is an environmental administrator for the Bureau of Radiation Control, a branch of the Florida Department of Health.

Mr. Keaton has been an employee of the Department for 33 years. The last 20 years, he has served as the administrator of the statewide environmental radiation surveillance and radiological emergency response programs. He has received the Hammer Team Award from former Vice President Gore and the Board of Directors Award for Outstanding Achievement in the field of radiation protection from the Conference of Radiation Control Program Directors, of which he is an associate member.

Additionally, he is a member and former two time president of the Florida Chapter of the Health Physics Society. Mr. Keaton was a member of the Technical Advisory Committee at the Florida Institute of Phosphate Research and Chaired the E-35 Marson Committee of the Conference of Radiation Control Program Directors.

Welcome to the subcommittee. You are recognized.

Mr. Keaton. I would like to describe today what the Department of Health's limited role is regarding naturally occurring radioactive material in the environment, and specifically as it is associated with the phosphate mining industry.

The U.S. Environmental Protection Agency has primary responsibility for developing rules and national standards for handling phosphogypsum and waste issues. The Florida Department of Environmental Protection, under the authorization from EPA, also looks closely at the proper disposal and beneficial use of this material. As part of the Department of Health's mission to promote and protect the health and safety of all residents of Florida, we have a limited role in the monitoring of phosphogypsum. Through our Bureau of Radiation Control, we regulate the use of radiation and radioactive materials in medicine and industry. Please note, therefore, that our Bureau is only looking at the radioactive issues associated with phosphogypsum. We understand that there are also other environmental contaminants that can impact groundwater from the disposal and use of phosphogypsum, such as sulfates, sodium, iron, fluoride and trace heavy metals. These contaminants should also be evaluated when making beneficial use decisions about this waste.

The Bureau also has several environmental monitoring programs, including one that monitors the radiation levels on phosphate lands both before mining and after land reclamation. This program has been going on since 1986. The data we have gathered indicates a small--a very small--increase in radiation levels following reclamation of mine lands. However, please note that the pre-mined and reclaimed lands are not identical in makeup to the phosphogypsum, although there are many similarities, including the presence of naturally occurring radioactive materials.

Although the Department of Health does not regulate the

disposal or the use of phosphogypsum and has not been directly involved in research regarding the potential uses and possible health risks from the use of phosphogypsum, we do conduct some testing in the mining areas. Our staff have also served as advisors to FIPR to provide input on radiation related matters and advice on appropriate research areas. FIPR was established by the Florida Legislature to initiate, conduct or sponsor studies to minimize or rectify any negative impact of phosphate mining and processing on the environment and improve the industry's positive impact on the economy. FIPR is a public entity located within the Florida Department of Education.

One aspect of our direct involvement in assessment of health risks from naturally occurring radiation in the phosphate mining areas is the risks from indoor radon levels. In an effort to control indoor levels of radon, both the EPA and the State of Florida began developing mitigation techniques to be used in existing buildings.

In 1978, the State also embarked on a project to develop radon-resistant construction techniques for new homes built on reclaimed phosphate lands. Standards for new construction and the mitigation of radon in existing construction were developed between 1989 and 1995 by the Department of Community Affairs. These standards, called the ``Florida Standards for Radon-Resistant Construction'' are also included as appendices of the Florida Building Code. Again, although this effort is not directly related to the use of phosphogypsum, it shows that research can be performed and efforts can be taken to mitigate the risks associated with naturally occurring radioactive material and ensure that risk is at a safe level.

Studies of phosphate workers have not shown abnormal cancer rates and health reviews of populations living in previously mined areas do not indicate an increase or excess of lung cancers. More extensive research about the effects of exposure to phosphogypsum is needed.

In conclusion, it also makes sense to aggressively research appropriate and safe uses for this plentiful product. In Florida alone, we have approximately 1 billion tons in 24 stacks, with an annual product of 30 million new tons of phosphogypsum. We are interested in any scientifically valid research that shows possible health risks or lack of health risks associated with potential uses of phosphogypsum. We believe this is a significant issue that we could understand better through more research, research that can enable us to determine appropriate uses for this material and what steps are needed to protect the public's health and the environment.

We believe that the current practice of stacking the phosphogypsum has potential environmental and public health risks, as evidenced by unintended releases and spills and the recent need to dispose of millions of gallons of gypsum and acidic wastewater. Last year, the Federal Government granted the DEP permission to dispose of the treated wastewater in the Gulf of Mexico. We therefore support and encourage aggressive research to determine safe uses of phosphogypsum, while protecting the health and safety of the residents of Florida. Through this research, developments may allow for better roads, more efficient landfill covers, additional needed sulfur for the soil, and construction materials like safe glass, thereby providing a residual benefit to society.

I am happy to answer any questions that you may have.

[The prepared statement of Mr. Keaton follows:]

[GRAPHIC] [TIFF OMITTED] T5739.039

[GRAPHIC] [TIFF OMITTED] T5739.040

[GRAPHIC] [TIFF OMITTED] T5739.041

Mr. Putnam. Thank you very much, Mr. Keaton.

Our third witness for this hearing is Mr. Dick Eckenrod. Mr. Eckenrod is the executive director of the Tampa Bay Estuary Program.

Since joining the Tampa Bay Estuary Program in December 1990, Mr. Eckenrod has directed the development of an innovative management approach for Tampa Bay that seeks to balance economic and environmental concerns.

Before coming to TBEP, he was part of an inter-disciplinary team of scientists and engineers employed by the Southwest Florida Water Management District.

From 1984 to 1987, he advised the Manatee County Commission on natural resources issues as director of the Department of Land and Natural Resources. His responsibilities included mining regulation and management of county-owned conservation areas. He served the county as phosphate mining coordinator from 1980 to 1984.

He has also worked in the private sector as a specialist in water quality management and environmental impact assessment and an environmental engineer with various consulting firms.

A member of the Water Environment Federation, Mr. Eckenrod serves on the Executive Steering Committee of the Agency on Bay Management and a number of other environmental advisory and coordinating committees in the Tampa Bay region.

Welcome to the subcommittee. And you are recognized.

Mr. Eckenrod. Thank you, Mr. Chairman, for this opportunity to address the subcommittee on the subject of beneficial uses of phosphogypsum and some of the environmental issues associated with those uses. I am Dick Eckenrod, executive director of the Tampa Bay Estuary Program.

Tampa Bay is 1 of 28 estuaries of national significance participating in the NEP established pursuant to Section 320 of the Clean Water Act. Tampa Bay was designated an NEP in 1990 by President George Bush and has subsequently developed a cleanup and restoration plan for Tampa Bay. That plan is now being implemented by the program's partners in the public and private sectors.

The Estuary Program is an independent special district of the State of Florida, organized through an Interlocal Agreement under the authority of Section 163.01 of the Florida statutes. The nine-member governing body of the Estuary Program, known as its Policy Board, consists of elected officials or senior administrators from the cities of Tampa, St. Pete, Clearwater, the counties of Hillsborough, Pinellas and Manatee along with U.S. EPA, the Florida Department of Environmental Protection and the Southwest Florida Water Management District.

The Estuary Program does not generally take positions on environmental permits or other regulatory matters, but does endeavor to serve as a source of reliable information and unbiased advice to all interested parties. It is in that spirit that I offer the following comments.

Among the priority issues addressed by the Estuary Program are controlling excessive nitrogen loading to Tampa Bay in order to maintain water clarity and foster expansion of submerged aquatic vegetation or seagrasses in the bay; reducing chemical contamination of bay sediments and protecting relatively clean areas of the bay from contamination; and developing a long-range dredged material management plan for the bay that will minimize adverse environmental impacts and maximize beneficial uses of dredged material.

Reusing or reclaiming liquids and solids that in the past were considered waste materials and threats to the bay is a key element of the Estuary Program's strategy to achieve its water

quality and habitat restoration goals. The Program's local government partners, for example, have made major strides toward nitrogen load reduction by reclaiming domestic wastewater for irrigation of residential, commercial, agricultural and public properties. In addition to reducing nitrogen loadings to the bay, reclaiming wastewater is helping offset demands on ground and surface water supplies for public use.

Another Estuary Program partner, the Corps of Engineers, is selectively using dredged material from ship-channel construction and maintenance to create emergent wetland habitats, restore eroded beaches and improve the quality of submerged habitats in previously disturbed areas. Sediments once regarded as spoils or wastes are now being transformed from environmental liabilities into environmental benefits for Tampa Bay.

Managing the huge and ever-growing inventory of phosphogypsum in Florida similarly offers opportunities as well as challenges. Using all or a portion of the estimated 30 million tons of phosphogypsum generated each year for safe and appropriate uses could reduce the volume of contaminated process water that will ultimately need to be disposed of. And, as the recent experience at the Piney Point facility in Manatee County has shown, reducing the volume of stored process water also reduces the potential magnitude of accidental releases. Options for beneficial use of phosphogypsum should be actively pursued along with the research needed to reasonably assure protection of public health and the environment.

In addition to potential impacts on nutrient loads, evaluation of potential beneficial uses of phosphogypsum in the Tampa Bay watershed should take into account toxic contaminants that have been documented at various levels of concern in Tampa Bay. An ecological and human risk assessment conducted for the Estuary Program by Parsons Engineering Science in 1996 concluded that polychlorinated biphenyls, polycyclic aromatic hydrocarbons and specific metals--chromium, copper, mercury, nickel and silver--were priority contaminants of concern in one or more segments of Tampa Bay. Potential human health and environmental risks of contaminants of concern associated with phosphogypsum should also be thoroughly assessed before specific uses are approved.

In summary, beneficial uses of materials formerly regarded as wastes are now making important contributions to the recovery of the Tampa Bay ecosystem. Potential beneficial uses of phosphogypsum should be similarly explored, together with appropriate health and environmental risk assessments.

That concludes my prepared remarks.

[The prepared statement of Mr. Eckenrod follows:]

[GRAPHIC] [TIFF OMITTED] T5739.042

[GRAPHIC] [TIFF OMITTED] T5739.043

[GRAPHIC] [TIFF OMITTED] T5739.044

Mr. Putnam. Thank you very much, Mr. Eckenrod.

And before we go to questions, I overlooked a small item when we were administering the oath. If the individuals who were sworn in outside of our seated witnesses would please rise and identify themselves and their title for the record. So everyone who was sworn in outside our witnesses, if you would please come to the front row and we will start on the left and identify by name and position or title.

Mr. Rosnick. My name is Reid Rosnick, I am an environmental scientist with the Environmental Protection Agency. I am in the

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Office of Radiation and Indoor Air in Washington, DC.

Mr. Putnam. If you could step forward, please, so that we can get this for the record.

Mr. Button. My name is Rick Button, I am a health physicist with the EPA, Region IV in Atlanta, GA with the Quantitative Technical Support Section.

Mr. Putnam. Thank you.

Mr. Burkee. I am Brian Burkee, I am a research director with the Florida Institute of Phosphate Research.

Mr. DeGrove. I am Bruce DeGrove, I am director of regulatory affairs for the Florida Phosphate Council in Tallahassee.

Mr. Posey. I am Stan Posey, manager of environmental affairs for PTS Phosphate at White Springs.

Mr. Putnam. Thank you very much, and we will begin with our questions.

Ms. Cotsworth, your testimony--you said that the concern of the EPA was to make sure that any increased exposure was justified and legitimate. Did anything that was presented in hearing one lead you to believe that there is a scientific basis for changing the treatment of phosphogypsum from being a waste product to being a commercial product?

Ms. Cotsworth. We would be happy to sit down with the members of that panel to discuss specifically the points that they made, to work with them to determine if there is sufficient early information that would support a petition to the agency under the regulatory authority that I cited, and to work with them, again, in terms of what we require for a complete evaluation and what we would require in order to be able to thoroughly assess and make again a publicly defensible and scientifically defensible conclusion or decision.

Mr. Putnam. So they have your commitment then that you and your people will meet with them and their people to do this?

Ms. Cotsworth. We would be glad to. I know there have been frustrations, I think on both sides, but we certainly would be willing to sit down and be as clear and specific and informative as we can be.

Mr. Putnam. Until 1989, phosphogypsum was treated as any other item of commerce and sold for agriculture and was used locally, as was discussed in the first hearing, for any number of construction projects. What was the basis for the shift in policy from an item--where an item of commerce was suddenly treated as a waste product and subject to regulation?

Ms. Cotsworth. We were implementing the requirements of the Clean Air Act to control the risks of hazardous air pollutants, and our source controls were established as the legislation requires us to do consistent with all hazardous air pollutants. And in the 1989 rulemaking, we advised the public that we had found a basis to require management in stacks because of the potential for it to be incorporated into other products and be defused throughout the country such that we would be unable to ensure that the rate on emissions did not present an unreasonable risk. That was the basis.

Mr. Putnam. And an unreasonable risk in your opinion would be one that exceeds 1 in 10,000?

Ms. Cotsworth. Generally yes, the risk range that we used consistently for Clean Air Act regulatory decisions is between 10 to the minus 6 which is one in a million risk to the 1 in 10,000 number generally. And that 1 in 10,000 is also a risk level that we use in many other of our regulatory programs.

Mr. Putnam. The risk analysis that you used employed an assumption of 70-year residency for occupants of the hypothetical home. That is a value that is not supported by any available data and shorter residency times are used by your agency in other risk calculations. So why was this item chosen

for the 70-year residency risk calculation?

Ms. Cotsworth. The 70-year residency is actually, again, consistent with the assumption that we use in risk analyses for all of our Clean Air Act rulemakings and for many of our other rulemakings and regulatory activities. There are some decisions where a 30-year residence time is included but for the regulatory purposes, we generally use a 70-year residence time. And we have data that suggests that it is not inappropriate to use for phosphogypsum and farmer residence time.

Mr. Putnam. You have studies that suggest that it is not inappropriate to use the 70--what studies were done to justify that action?

Ms. Cotsworth. We have conducted studies, I believe that were associated with the 1992 and possibly the 1989 regulatory actions. I would be happy to go back and research and submit those particular studies and statements for the record.

Mr. Putnam. Well, I am just trying--the Federal Register in 1989 does not specify a reason for the ban, so I think it is important to know what action--what studies precipitated that action. And Dr. Chambers, in the first hearing, stated that your own handbook uses a 30-year risk model. Could you explain that difference?

Ms. Cotsworth. I believe that the handbook that is being referred to is used in regard to cleanup decisions associated with our so-called Superfund program. I cannot absolutely say for sure, but I believe that is the reference. But in terms of most of our regulatory decisions, including those under the Clean Air Act, we do use a 70-year timeframe.

Mr. Putnam. For actions under the Clean Air Act, you use the 70-year timeframe. And is that directed by law or is that an internal rule?

Ms. Cotsworth. I believe it is an internal approach, I cannot state with certainty. I will be glad to again check into that and get back to the staff.

Mr. Putnam. Why would there be such a dramatic risk calculation for a Superfund site which can be anywhere in a community and, you know, through recent legislation on brown fields and everything else, subject to other uses--why would there be such a dramatically different risk calculation for that than there is for Clean Air Act compliance?

Ms. Cotsworth. Well, the difference is largely a cleanup, a remedial situation dealing with contaminants that already exist in the environment as opposed to rulemaking, national generic level rulemaking, which are intended to be protective and preventative in nature.

Mr. Putnam. The calculations that you did use averaged the amounts of phosphogypsum used for soil treatment in California and in fertilization in Georgia and arrived at an annual application rate of 1,350 pounds per acre per year. Is there a practical basis for that application rate that you all used? Are you aware of any farmer who uses that much phosphogypsum?

Ms. Cotsworth. The determination was based on data and information that was submitted to the agency and that is included in our background information document. And again, we were developing a national regulation, which is generic in scope and application rates across the country do vary, according to crop type, soil conditions, purpose of the application. And for us to be generally conservative and take into account the possibility of reasonable worst case exposure assumptions, we did use data and information provided from California in determining the application rates.

Mr. Putnam. Is there not an ability for you--you referred to the general application rate in a general generic rule to be applied nationwide. Is there not a basis for you to develop or promulgate a regional rule that would apply to sodic soils in

the western United States and a different one that would apply to the treatments that are used in the southeastern United States, just as other aspects of EPA promulgate different labels for different crops in different regions?

Ms. Cotsworth. It is possible; however, it becomes very difficult to implement, difficult to enforce and it transfers, in large part, the burden of implementation to the farmers and the small agribusinesses that would then have to spend the time and effort to be careful in regard to the use of a product as opposed to us regulating the content from the start.

Mr. Putnam. I appreciate your sympathy for the farmer and small business, but EPA has never hesitated to transfer that burden in the past.

The soil treatment and fertilization, two unrelated practices, why were those two unrelated practices used to justify the ban for fertilization? Again, would it not be reasonable to have a rule for fertilization and a rule for soil treatment?

Ms. Cotsworth. Again, as I just indicated, the agency concluded that in order to provide protection for the possible most reasonable worst case scenario, that it was not appropriate to make that distinction.

Mr. Putnam. That is a fairly subjective thing. How do you know what a reasonable worst case scenario is? I mean, if you use this high concentration for sodic soils but you only do it once and then you are done for decades, if not forever, and then in the case of the peanut growers, they are using it every third year, is it the judgment of EPA's scientist, is it peer reviewed? How do you come about determining a reasonable worst case scenario?

Ms. Cotsworth. It is based on a risk assessment that is conducted according to the risk methodology that is in general use across EPA. There may have been some changes in methodology improvements over time since the 1989 and 1992 rulemakings; however, the risk assessments that were conducted at that time were consistent with all of the agency's practices and policies regarding risk assessment, including the scenarios, media transfers and how to use our data. Those risk assessments are normally, as with all of our background documents, are part of the public docket that is associated with public comment and notice rulemaking. They should have been available for public review at the time of the issuance of both the proposed and the final regulations.

Mr. Putnam. Well, let us come back to Florida for a second. What is the basis for banning north Florida phosphogypsum for roads but not for agricultural purposes when the road bed use has a lower risk than agricultural use? In other words, you have said it is OK to spread it on the fields that in a rapidly urbanizing State have a high risk of being homes in our lifetime, but banned it from a road bed usage, which is probably--which is highly unlikely in this State and most any other. What is the basis for that?

Ms. Cotsworth. Well, we did evaluate, as I said, generically road building in the 1994 regulation and we did find that certain exposures would lead to excess cancer rates, in excess of the risk range that we specified, and that in fact road bed usage did have a higher risk than actually agricultural usage.

Mr. Putnam. What roads were you testing to make that determination, what tests, what studies indicated that the cancer rate--the risk rate would be greater?

Ms. Cotsworth. The studies are detailed in our 1992 background information document. I apologize, I cannot personally speak to the specific studies that are accounted for here.

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Mr. Putnam. Does your colleague know?

Voice. No, I am sorry, I do not. I would have to look through the actual background information.

Mr. Putnam. Well, could you do that while we move on and we will come back to you.

Mr. Lloyd, do you know what studies the EPA used for their 1994 rule?

Mr. Lloyd. Some of the things that are mentioned we have never been able to find in the BID documents, so I do not know. We would be interested in finding the data that we requested in 1995 as to how they did the risk assessments for the 1992 rule. We have never been able to get the documents to show what the actual calculations were and it would be appreciated if we could get them.

Mr. Putnam. Is that type of document available to the public, Ms. Cotsworth?

Ms. Cotsworth. The public record for that rulemaking should still be available. What I cannot personally attest to is whether the documents or calculations that were just referred to are in that rulemaking record. Again, we do have high standards for the documentation and technical support documents to be included in our public docket and in our--and referenced in our preambles to our regulations. I apologize that, not having been with that office when the 1989 and 1992 regulations were promulgated, and at this point I have not seen those entire rulemaking dockets to be able to say specifically whether what was just alluded to is there, but I would certainly hope so.

Mr. Putnam. I would hope so too and I will make this my official request for those records and supporting documents and working papers as well, and we look forward to receiving those.

Why does EPA make atypical assumptions when calculating risk assessments for phosphogypsum in the 1992 ruling that are as unreasonable as those used in the 1989 rule that require correction only after a successful challenge?

Ms. Cotsworth. Again, the regulatory process allows for public input, public participation, particularly in regard to the way our proposed and then final regulations are crafted, giving people the opportunity to comment on the technical information upon which our decisions are based. Certainly the additional input that was received by the agency post-1989 was found to be useful for making subsequent regulatory modifications and we always remain open to new information, new data for consideration as to whether we need to improve or change our regulations, or in this case, because we have a petition process, to be able to use the petition process to exercise regulatory flexibility.

Mr. Putnam. And how long does that regulatory flexibility usually take to work its way through the process?

Ms. Cotsworth. It probably takes longer than the petitioners here would have liked. And we have not approved any petition to date. In part, that is probably due to change over in our staff and lack of clarity for the petitioners as to what we really need in a petition application. In some part, it is also due to the amount of time that it has taken for petitioners to respond to our data requests and our requests for more analyses.

Mr. Putnam. And do you know how long it took them to respond to your requests, the petitioners? How long did it take for them to respond to your requests for additional information?

Ms. Cotsworth. I believe in some cases there has never been a response and in some cases, it has taken many months.

Mr. Putnam. And with regard to Dr. Shieh's request for a permit to move forward with phase III, that was a 4-year and

still counting pending request--it seems to me this is unnecessarily adversarial. You have a group of credentialed, published, highly regarded scientists pursuing a line of research. In other words, they are seekers of information, of knowledge, of hopefully a solution to what we believe is a problem in the stacks. It would seem to me that at bare minimum for research purposes, the EPA would embrace that type of search for knowledge. Recognizing your own limitations as an agency and personnel constraints and funding constraints and everything else and the myriad of environmental issues you have to deal with, it would seem that when you have a group like this, and undoubtedly they are not the only ones, that that would be something that you would really embrace and join hands and move forward to solve an environmental problem.

I mean, I think everyone would admit that is not really how it is. I mean it has become this adversarial issue for years. I mean it predates me but as recently as 5 years ago in the legislature when we tried to work through this. You can never find anybody to give you an answer, you can never find anybody that seems really interested in working to make it work. And that is the rub, that is the real frustrating part here.

We have all kinds of questions here about why things went the way they did and why they have not been answered and why we are waiting 4 years just to be able to dig a plot to research landfill material. I mean we are not talking about cancer drugs here, we are not talking about distributing something to every mouth in America, we are talking about allowing research to go forward. And for some reason, whether it was you or your predecessor or the agency's culture, there is this adversarial issue. Help me understand that or please convince me that is not the case.

Ms. Cotsworth. I agree, it has been adversarial and what I believe and I believe the new administrator wants to make sure is that there is collaboration and honest dialog. You talked about the 4-years for review of Dr. Shieh's petition. Last June, members of my staff came here and had a meeting and basically indicated that what we had already in hand did not discuss the very issue of most concern to us, which was radioactivity. We have had a resubmission, additional information since December of last year, and we are actively reviewing that petition right now and at the same time trying to develop useful and clear guidance for all the petitioners in regard to what we expect relatively to again a complete application and one that will then support a final and clear decision.

I too believe that the process should be finite in terms of time, it should be transparent for everyone, the petitioners as well as others, including the general public who may have an interest, and that a decision is rendered. It may not necessarily be the decision that someone wants but I want to be able to give someone a final yes or no answer on the petition and to be able to tell them clearly why it was the answer that it was, so that they can understand and that we can again defend it in the public view and it will withstand scientific and technical challenge.

Mr. Putnam. There clearly are a lot of reasons why this has become a problem. But a change of administration is not one. When you look at the EPA and the number of employees that change from administration to administration, no matter who the President or the Administrator is, it is minimal. I mean this is a professional staff issue. The political appointees are not running road tests, road bed tests on radium-226. Regardless of who the Administrator is or who is in the White House, there ought to be some cultural openness to research and the search for answers.

Prior to EPA's 1989 rule banning the use of phosphogypsum, EPA conducted public hearings on whether or not to put layers of soil on top of the stacks to reduce the radon emanation that might be harmful to the people living in the vicinity of the stacks. Those public hearings concluded that the risks did not justify that action.

Now if the risk of having a multi-million ton concentration of phosphogypsum did not justify sprinkling top soil over it to reduce radon emanations, why would the risks exist in sprinkling phosphogypsum in central Florida agricultural fields or in building a road bed out of it?

Ms. Cotsworth. I am not personally aware of the public meetings or hearings to which you refer. So I am unable to comment on that. But certainly as we consider additional uses, we have to look at a variety of scenarios and pathways through which people are exposed. And the presence of phosphogypsum in roads and agriculture can sometimes present different exposures than stack management and each one needs to be evaluated accordingly and appropriately.

Mr. Putnam. But you said radioactivity is the real issue. I mean that's really the issue.

Ms. Cotsworth. Right.

Mr. Putnam. And so 40 million tons stacked, to me just common sense would say that radioactivity would be a greater issue in that concentrated form at that scale--that has to be a larger issue than when it is evenly spread in a road bed or on an agricultural field. And these are from the public hearings that your agency had prior to the 1989 rule.

Ms. Cotsworth. Again, I am just not familiar with those public hearings and the situation that is being described, but again, it is looking at different exposure scenarios and certain management controls that are in place relative to the stacks that would not be present in other uses.

Mr. Putnam. You were provided these questions in advance of this hearing.

Ms. Cotsworth. That is right, and between Friday afternoon and today, I could not find any reference to the hearings that were mentioned.

Voice. Congressman, I could provide some light on that question.

Mr. Putnam. Please. Speak into the mic, come forward please and speak into the mic.

Mr. Button. Richard Button. With regard to the soil on top of the stack, what we found is that on a stack, due to weight and volume, it creates its own cap, so putting soil on top of a stack does not reduce the radon emissions any more. And we find that the radon emissions tend to be greater on the side where the cap is broken up, which would explain why if you spread it out on farmland, the radon emissions would be higher than or equal to what they would on top of the stack.

Mr. Putnam. Thank you.

When did EPA last visit the phosphogypsum stacks to get a read?

Ms. Cotsworth. I believe staff from my office, during their visit in June of last year, actually visited a stack.

Mr. Putnam. And did you test their level of radiation?

Ms. Cotsworth. It was not a compliance visit or any kind of enforcement visit, it was for the purpose of information sharing relative to the petition process and getting a better understanding and appreciation of the problem and the issue.

Mr. Putnam. And as part of that information sharing, did you all test the stack?

Ms. Cotsworth. No, not that I am aware of.

Mr. Putnam. Mr. Lloyd, do you know if they tested the stack while they were here?

Mr. Lloyd. The stacks were last tested prior to 1989, as Rick can attest to.

Mr. Putnam. And not since then?

Mr. Lloyd. Not at all that I know of.

Mr. Putnam. If radioactivity is the issue, and we have 24 stacks around the State, it is not a big enough issue to have an ongoing radiation testing program?

Ms. Cotsworth. The NESHAPS that I referred to has been delegated to the State of Florida and I believe any monitoring would be conducted by the State. We have not--and I will look to Dick for some confirmation on this, I do not believe we, EPA, have done any oversight inspection or testing.

Mr. Button. That is correct.

Mr. Putnam. OK. You are from the air quality/radiation piece of EPA, is that correct?

Ms. Cotsworth. Yes, I am.

Mr. Putnam. Is there another piece of your agency that deals perhaps with water quality that is concerned about the concentration of these stacks and the Piney Point incident and the potential ecological hazard that stacking phosphogypsum presents?

Ms. Cotsworth. I think it is safe to say yes, we are all concerned about what happened last year at Piney Point.

Mr. Putnam. Well, but it seems to me that your piece of the EPA has determined that--at least in 1989, you determined that it is safer to stack it up than it is to spread it out. But is there another office in another wing of Atlanta's regional headquarters or some place in Washington where the water quality people are saying we have a real problem here. We have hundreds of millions of gallons of acidic water building up in these stacks that we might need to do something about. Is there coordination within EPA between air quality and water quality as it relates to gyp stacks?

Ms. Cotsworth. There is within the regional office, which was the group that dealt primarily with the Piney Point situation. I know Mr. Button here was involved as well as our Region IV emergency response personnel. I have not been approached by the EPA water office in regard to phosphogypsum during the time that I have been office director. But I would certainly not only coordinate with other State and appropriate agencies in regard to a phosphogypsum use application, but I would have to consult with my counterparts across EPA in terms of any concerns or issues that would arise that deal with their statutory responsibilities and the programs that they implement.

Mr. Putnam. Mr. Button, could you please come back to the microphone, since you were part of the emergency response to gyp stack management that occurred last summer?

Are you aware of a multi-disciplinary approach to managing these?

Mr. Button. Yes, when Superfund emergency response in Region IV Atlanta, they were asked by the State of Florida to provide assistance and when they found that phosphate plant had some low level radiation, I met with them and talked with them and gave them some input on the radiation risk associated with it, and also talked to their water people and everybody else that could provide input for their response.

Mr. Putnam. Are you aware of any reports that the water people, as you put them, any conclusions that they arrived at that perhaps managing the stacks as we do today might not be the best approach from a water quality perspective?

Mr. Button. No, I am not, but the Superfund emergency response people may be. I am not aware of that.

Mr. Putnam. Could you please, when you get back to the office, see if that information exists? I would like to make

that official information request.

Mr. Button. Yes, I can do that.

Mr. Putnam. So we can review their conclusions as it relates to their opinion of our management of phosphogypsum stacks.

Mr. Button. Well, they officially made a decision to dump the water into the bay, so I'm sure there is some documentation to support that. So yes, I can followup on that.

Mr. Putnam. And assuming another rainy season, we might have to dump some more into the bay. So it becomes an ongoing water quality environmental hazard that does not appear as being necessarily shared with the air quality folks. Thank you.

Mr. Keaton, in your testimony, you mentioned that the State of Florida developed standards for radon resistant construction. Could you describe those in some detail and tell us how or if they might foil the 70-year residency assumptions that EPA used in their risk calculation?

Mr. Keaton. Let me caveat that by saying there was a lot of work going on at the time. The Florida Institute of Phosphate Research had a program where they were doing mitigation in homes, they actually built some homes. Florida and the Environmental Protection Agency at that time were developing mitigation techniques and eventually that turned into a project where new construction was to be used on reclaimed phosphate lands.

What basically these construction techniques do is prevent radon--or at least reduce it significantly from getting into the home and also lowering through the slab and elevated crawl space, lowering the gamma levels that could possibly be in a home. So these techniques would be very effective if you were to build a home on phosphogypsum or reclaimed phosphate lands.

Mr. Putnam. Does the Department of Health conduct their own risk calculations in the everyday work of your oversight of health and safety issues for the State?

Mr. Keaton. We do when there is an emergency situation, when we see major problems. There has been a lot of work that has already been done in this area, especially on the workers at the phosphate mines. We have looked at areas like the Cornet, I am sure you are familiar with that, we have also looked at Stouffer Chemical, these areas, and have not yet to date found elevated levels.

As far as an area-wide study on all the people in this area; no, that has not been done. But by that same token, we have not seen any levels that would indicate that would necessarily need to be done.

Mr. Putnam. But could you please refresh my memory on what you found in your health studies of the phosphate workers in populations living in the previously mined areas?

Mr. Keaton. They did not show any increase in lung cancers or any health effects. As a matter of fact, there were many studies done, there was--I have them here--I mean I do not have the studies, but I have the information, if you would like to have it.

Mr. Putnam. We would. Could you please, if you would, tell us if you believe the differences in the north and central Florida phosphogypsums are significant enough to allow the use of one and ban the use of the other?

Mr. Keaton. Well, there is a radiological difference, but we are looking at very low levels of radioactivity. The Environmental Protection Agency has done risk assessment on that and these are models. OK? You put information in, you get information out. If you look at these models and you change the parameters that you use, it would seem that from what we have seen from the SENES reports that, no, there may not be a problem.

What we would like to see is the EPA and the FIPR come together on this and make decisions on what uses and what risks are going to be acceptable and we can go from there.

Mr. Putnam. You know, let me perhaps go to one of our scientists. Again, help us understand the difference between the north Florida and central Florida in terms of the number of picocuries and what that really means in the context of atmospheric radiation or just inherent radiation that exists today. Give us some context for that, if you would.

Mr. Chambers. I will try first. I am sure Mr. Lloyd or others will correct me.

I believe north Florida has a radium content in the order of 10 picocuries per gram and central Florida phosphate perhaps might be 26-27, something like that. So that is about two and a half times the radium-226 content. All other factors being equal, the rate of release of radon would be proportional to the concentration of radium-226. And that is why it is so important in looking at these risk assessments, whether it is EPA's or ours, to be reasonably conservative but not unrealistic or not unreasonable. And I think it was quite clear from Dr. Sumner's discussion this morning that there is a practical upper limit on the rate at which phosphogypsum might be applied, for example, to a farmer's field. And that is, for example, a ratio of 2,700 to 900, 2,700 being the upper 95 percentile as determined by EPA. That is larger than the difference in the radium-226 content.

So basically with any reasonable application rate and even following EPA's methodology, there should be no practical difference in the risk that would result from radium and radon.

Mr. Putnam. And Mr. Lloyd, do you or anyone with you have any additional information on that as it relates to how that compares to other activities that might lead to radiation exposure?

Mr. Chambers. I will come back to that as well. I do not have my litany of comparisons in front of me. I think I said earlier that at my age, I have a risk of about one in a million dying from natural causes during this hearing. In any event, if you look at EPA's risk range of 1 in 10,000 lifetime, that is approximately equivalent to one in a million risk per year. So my 1 hour or 2 hours here from natural causes would be a risk of one to two in a million of passing away from natural cause during this hearing.

Similarly, if I was a smoker, and I am happy I am not, smoking somewhere between one and two cigarettes, that is all it takes, would be the kind of risk that you would get, that would result in a risk of one in a million. Similarly, if I was flying from Tampa to Colorado to go skiing and return, that kind of flight would incur an extra radiation risk in the order of one in a million. Here, the extra radiation is from outer space from cosmic rays, because as you go up in the air, higher in the altitude, the protection from the air from outer space cosmic rays is less. So basically a risk of one in a million is about the same as my chances of dying, it is about the same as a return flight from Tampa to Denver, it is about the same as smoking a cigarette or a cigarette and a half.

Mr. Putnam. A cigarette per year?

Mr. Chambers. No, one cigarette.

Mr. Putnam. In your lifetime.

Mr. Chambers. That is a risk of one in a million.

Mr. Putnam. Let me see if I can shuck the corn a little bit here. [Laughter.]

Are you saying that if you did stay in a house 18 hours a day, 7 days a week for 70 years and if you employ this model that EPA has constructed for phosphogypsum, even if you did do those things, it is the equivalent exposure to radiation as

flying from here to Colorado to go snow skiing?

Mr. Chambers. Plus or minus the uncertainties, I believe that is about correct.

Mr. Putnam. So even if you do employ their maximum risk model, you are still talking about negligible risk compared to every other normal activity.

Mr. Chambers. Yes. As I indicated earlier, I feel that yes, there is a risk, it is a theoretical risk, but to me it is incredibly small and from my perspective, of no consequence because you are looking at an annual risk of about one in a million which converts to a lifetime risk of 1 in 10,000 and that is what we are regulating this industry to.

Mr. Putnam. Ms. Cotsworth, is that the typical benchmark that you all use in promulgating rules?

Ms. Cotsworth. Basically our decision is consistent with the approach that the agency takes in regard to its regulation. Our philosophy is that regardless of the background and the risks that already exist, that we are required to take action to prevent additive additional risk over and above what people are already exposed to.

Mr. Putnam. Additive risk----

Ms. Cotsworth. Any incremental risk that is within our purview, we try to control.

Mr. Putnam. Any additive risk above 1 in 10,000, greater than 1 in 10,000, or any additive risk?

Ms. Cotsworth. Any additive risk. We look at an excess cancer rate of 1 in 10,000 as the basis for possibly regulating.

Mr. Putnam. Is that an internal decision or is that set by law?

Ms. Cotsworth. In regard to, again, radionuclides as a hazardous air pollutant, there is a long history regarding the Clean Air Act implementation, the so-called benzene rule, court decisions that indicate that the agency is appropriate to be looking at excess risk in terms of 10 to the minus 6 and 10 to the minus 4 range and applying a margin of safety. So that has been defended both in court and in other regulatory decisions.

Mr. Putnam. But you just said that you all attempt to control any additive risk, even I assume lesser than that 10 to the minus 6.

Ms. Cotsworth. Right, we actually look at a range of one in a million and very often we back off from that to the 1 times 10 to the minus 4. In some cases, 3 times 10 to the minus 4. It's not an absolute hard line but it is generally 1 times 10 to the minus 4 in our regulatory decisions.

Mr. Putnam. I am sorry, go ahead.

Ms. Cotsworth. No, that is fine.

Mr. Putnam. Do you believe that their research is correct, that their findings on the risk are what they say they are?

Ms. Cotsworth. I would like to have the opportunity to look at it more thoroughly and look at the assumptions that were used, again, the scenarios to see how the studies and the research do compare against the risk assessment methodology that we used. It sounds intriguing.

Mr. Putnam. And if that is the case--well, I think they are dying to share it with you. But if it is correct, would that be the basis for changing the rule--would that be an adequate basis for changing the rule? Is their research adequate or do you have to go back to EPA and duplicate their research or do you accept them as accredited, certified, legitimate researchers?

Ms. Cotsworth. We would--I would not be able to say yes, we would revisit the regulations based on what I have heard today. We do not at this point have what we consider to be sufficient and compelling reproducible data and information that suggests

the need to completely overhaul the regulation. We are open to receiving data and information and assessing whether it is sufficient and adequate. We also encourage people to use the petition process that we have already set up. Since the regulation development process in the agency probably takes at least 5 years, the fact that we have an administrative option that is built into the current regulations, the agency has a preference, as I believe I stated before, for using the administrative procedures that are available to provide the flexibility and the relief on a more site-specific or region-specific, use-specific basis. And therefore not undergoing the very long laborious regulatory change process over which there is no control as to the outcome.

Mr. Putnam. Do you have a list of the information that they have not submitted or that you believe is insufficient, that they could check off. These are the things that EPA definitively says they must have? Do you have that?

Ms. Cotsworth. We have correspondence with certain individuals in the record. We are working at the same time as we are processing the current petition, Mr. Rosnick, who is behind me, is the staff person assigned to that, and he is also, by virtue of reviewing that petition, trying to develop a quick, easy-to-use, simple guidance, probably no more than a fact sheet, that can more readily and clearly indicate what are the requirements that we have for, again, a complete application, which then can be thoroughly evaluated.

Mr. Putnam. Is the definition of a complete application a moving target? Is that what I am hearing you say, that you are trying to put together a fact sheet, but as of now, nobody really knows what meets your definition of complete?

Ms. Cotsworth. The requirements that are in the regulations are very limited in their definition. We are trying to provide the definitiveness that the petitioners need, and again, based on our experience with working with the petitioners, they do need additional guidance from us as to what are the elements of the petition that are of most concern to us. As we indicated last June when we were here, we really want to know about the radioactive content and the issues related to that. We want to see if there is possibly any monitoring information that could be used to evaluate whether there are any other environmental hazards posed by the activity, the use or the research.

I agree it would be ideal if that guidance had been prepared some time ago. I cannot tell you why specifically it has not been, but it is important enough for me and my management team in the Office of Radiation and Indoor Air to say that this year, we want to provide our petitioners with good guidance so that they can develop a petition that is as quickly as possible able to be declared complete and then is ripe for that technical evaluation. And we commit to working and being in dialog with the petitioners, so again, they can clearly understand, as opposed to hearing it from, you know, a letter subsequently in terms of additional needs that still need to be met.

Mr. Putnam. So you certify that their application is complete and then you have to go evaluate it on its technical merits?

Ms. Cotsworth. Yes.

Mr. Putnam. And where would you do that analysis? You don't have phosphogypsum in your office in Atlanta, you don't have it on Pennsylvania Avenue, so what laboratory does that occur in?

Ms. Cotsworth. It may or may not occur in a laboratory. A lot of the review would be actually, again, evaluating and reviewing the documentation and the information that has been submitted on paper. We probably would want to come and visit with the petitioners and see some of the situations that they

are talking about, we would ask what kind of monitoring data they have and can make readily available to us, what kind of monitoring information perhaps the State regulatory authorities might have. But we do not necessarily use a lab, but we will use, again, risk assessment methodologies----

Mr. Putnam. So if you certify it as complete and after visiting with the petitioners, it would be their research that you accepted after some review--if you certified it as complete and you made that determination, you would not recreate the wheel, you would work off of the research that has been done in Florida, is that what I am hearing you say?

Ms. Cotsworth. That is right. And we might suggest some--as I believe was alluded to earlier, perhaps some controls, institutional controls, that might, in conjunction with the data and the science and the information, serve to again ensure that there is no unacceptable risk, that the risk is equivalent to the risk that the stacks pose right now, and go into our decisionmaking.

Mr. Putnam. The fundamental policy you are working off of, correct me if I am wrong, is that the stacks are inherently safer than any of the alternative uses proposed.

Ms. Cotsworth. As of this time, yes.

Mr. Putnam. And so the standard that the petitioners----

Ms. Cotsworth. When they are managed in accordance with current regulations.

Mr. Putnam. OK. The standards that the petitioner must then rise to is not that the alternative use is safe, but that its benefits outweigh the benefits of keeping it stacked up behind us here, is that correct?

Ms. Cotsworth. We look at the benefits. It has to be equivalent in terms of the risk. We look at risk to human health and the environment and it has to be in a way that we can translate to safe and protective of human health and the environment, which is no greater than a 1 times 10 to the minus 4.

Mr. Putnam. But they have to prove though that it is a better use than the being stacked up, not just that it is effective and safe in the landfill, not just that it is safe and effective in a road bed, not just that it is effective and safe as an artificial reef or in a glass container on a rocket to Mars. They have to prove that it is better than being stacked up, because that is the fundamental policy that you are weighing against.

Ms. Cotsworth. It has to be a use that is beneficial, a use for which there is a market, that there is a----

Mr. Putnam. Or that a market could be created from, whether there is an existing market.

Ms. Cotsworth. Or that we have some reasonable assurance that a market could be created for. There are situations in regard to other wastes that I am aware of where not all uses would be considered beneficial and legitimate.

But our bottom line is the risk.

Mr. Putnam. Are you familiar with something called PATHRAE?

Ms. Cotsworth. It is a model that my office relied on in regard to I believe the 1992 and subsequent rulemakings. That is as much as I know about PATHRAE.

Mr. Putnam. So it is the EPA's model for risk assessment, or it was at least in 1992.

Ms. Cotsworth. It is a model I believe. I may be able to ask--I know it is cited in this document. I apologize, I cannot go technically any further in discussing PATHRAE.

Mr. Putnam. But it is the model that you used to promulgate the rule in 1992, it is the research model that you used, correct?

Ms. Cotsworth. It was used. I cannot tell you whether it

was the only model or not, but it was used.

Mr. Putnam. But you used it, so we assume that you would accept it, it is a pretty good model if you used it in 1992. Has any of this additional research been done using the PATHRAE model so that we could compare apples to apples, Dr. Chambers?

Mr. Chambers. If I might comment. In 1998, it was, I believe, we did a very detailed risk assessment for FIPR on using phosphogypsum for roads and agriculture. And as a first step, we thought we would try and benchmark our models against the models used in the 1992 BID and there were in fact two models, PATHRAE which is referred to as a multi-media pathways model, it takes air and soil ingestion; and I believe in some cases EPA complemented the PATHRAE model with a model called MicroShield, which is another widely used model for gamma radiation.

I do not have time here, but with some effort, we actually had some difficulty in tracking down the actual inputs that EPA used, but we were able to, in the end, reproduce their 1992 BID results plus or minus a few percent. So as a first step, we did reproduce them.

Then basically, because these models were quite awkward to use, we did a screening calculation using other regulatory models. We continued to use MicroShield plus also the models by NRC which were a bit more advanced at the time and easier to use, and for the same inputs, we could benchmark those also to the earlier PATHRAE. When we did a screening using the NRC models, we again came up with the same conclusions that the other pathways were negligible and it was really radon and gamma that were the issue.

So yes, we have been able to test them. We can, with the same assumptions, reproduce the EPA's numbers.

Mr. Putnam. Ms. Cotsworth's concern is that the models that are being used in this research may differ from EPA or may make certain assumptions that would not be the assumptions that they would make if they were running the same risk calculation. I am paraphrasing you, but what have you done in your research to ensure that it is something that the EPA would accept, that the models are credible, that they are using the right assumptions and that it is good science?

Mr. Chambers. There is a whole history to this. As I mentioned before, we were able to benchmark our model. By benchmark, I mean get the same results for the same inputs to the EPA's models. And then to move forward, we did more than EPA with regard to pulling together information that is relevant to the situation in Florida for the soil application rates, road construction methods, house construction methods, indoor radon as it relates to soil radium-226 levels. And this is actually based on data that is documented in our report. I quite strongly believe that if we had the opportunity, we could convince EPA quite readily that our models were reasonable. It might be more difficult to convince them that our assumptions are appropriate; for example, the 70-year residency and this kind of thing.

However, I would like one final comment, to add that there is an inconsistency within even the radiation side of things between 70 years and 30 years, but also between Office of Radiation Programs and Office of Solid Waste. As I mentioned earlier, in 1999, when EPA did an examination of potential hazards from using fertilizer, they actually used a farm residency of 17 to 18 years, which is yet a different number.

So I think--I believe we can demonstrate good science behind our models and indeed EPA is moving toward the kind of modeling that we did, which uses Monte Carlo calculations to take account of uncertainties and I think EPA is moving in that direction. I think where the bigger challenge might be is

arguing or discussing what the appropriate assumptions are, and residency, for example, is one of them.

Mr. Putnam. So could you please clarify again what you do for the United Nations? That was in your biography, about the UNSCEARs?

Mr. Chambers. The UNSCEAR is the United Nations Scientific Committee on the Effects of Atomic Radiation was created in about 1955 by the United Nations, and I believe there are 26 countries, could be 27 including the United States and Canada and Britain and Germany and Russia and Japan and China, etc. And the responsibility of this group is to periodically--typically every 4 to 5 years--review all of the new verified, published, refereed research on the occurrence of radioactivity in the environment, and most importantly the health effects. This includes dosimetry and epidemiology. These documents are produced every 4 to 5 years and are used and referred to frequently by the U.S. National Council on Radiological Protection, by the U.S. EPA for that matter, by the International Commission on Radiological Protection, to whom the EPA often refers.

And it is an honor, but it is an agony. Consultant is basically volunteer time and my task right now is to revise, actually write the next UNSCEAR report on radon health effects.

Mr. Putnam. So we are not talking about some fly by-night backyard outfit here, we are working for the United Nations. And coming from the Congress, that can be sort of a frustrating group to work with, so you are to be commended for doing it.

But the models that you have developed, the work that you have done is often referred to by EPA, is that what I heard you say?

Mr. Chambers. The kinds of models that we have used, which include Monte Carlo calculations, which take account of uncertainty, have very much been used by EPA, and EPA I believe is moving more toward more routine use of these models because I am different than my colleague beside me, I may eat more, I am bigger, I may breathe more, and these models allow you to actually take account of difference in breathing rates and weight and this kind of thing. And it is the state-of-the-art that we have in modeling today.

Mr. Putnam. Thank you. The Tampa Bay Estuary Program coordinated a conference call for the EPA with more than 30 marine scientists to review the Piney Point situation that resulted in a unanimous consensus for the Gulf discharge plan. If we had heavy rains, if we had another Piney Point situation occur, would the Estuary Program support a similar decision and in reviewing that situation, what were the program's recommendations for ways to avoid a similar situation in the future?

Mr. Eckenrod. The request from EPA was whether or not the group of experts that we convened believed there was greater risk in disposing of a portion of that accumulated and partially treated wastewater offshore versus continuing to discharge into Tampa Bay. We consulted with marine experts from around the Gulf, experts in harmful algae blooms in particular, and the consensus of that group was that there was less risk in moving that water offshore than there was allowing that continued accumulation of that water in the stacks at Piney Point, or alternatively, discharging it into Tampa Bay. Both of those were options.

There was no--I think the groups that I have been working with and the Estuary Program has been working with, and that includes the Agency on Bay Management in Tampa Bay, we all, you know, share the belief that we need to take every reasonable measure possible to avoid occurrences like Piney Point in the future. And that is part of the reason I was interested in

participating in this hearing today, to share that concern and encourage this group to pursue, and EPA to actively pursue these beneficial uses of phosphogypsum to the extent that it can help reduce risk like Piney Point in the future.

Mr. Putnam. From your perspective, do you believe that the environmental risk associated with stacks is greater than the risk of dispersing the stacks throughout the State amongst the alternative uses that have been illustrated, is it a greater risk to leave them stacked up?

Mr. Eckenrod. Well, it is a difficult question for me to answer, not being an expert in radiation and obviously there are many people that have spoken today who do have that expertise. I can only say, Congressman, that based on the testimony I have heard, there is certainly expressed many potential uses of phosphogypsum that offer the hope that the risk would be--by making use of those opportunities, the risk could be reduced below what the current technology provides for; that is, stacking it.

Mr. Putnam. Dr. Sumner, do you wish to add anything to what we have heard in terms of the models that have been used and the work that you have done and others have done and this acceptability to the EPA?

Mr. Sumner. Mr. Chairman, I have been in this game for 45 years and I have had all the research work I have ever done reviewed by my peers, and I find it is an insult to hear that any of the research that I am accredited in my report or that I might have done myself is suspect. Scientists work according to given rules and our science is the best available.

So in my report, there is no fiction. This is the fact of the matter as we know it today. There might be some holes in it, we do not know, but those are facts. I want to say that first.

Second, I want to interject a little bit of common sense into this discussion here today, Mr. Chairman. In the old days, we used to use single super phosphate, which was composed of calcium dihydrogen phosphate and calcium sulfate, gypsum, in a 50/50 mix roughly, roughly 50/50. So in the old days, if the engineers had not got to us and decided we needed high analysis fertilizers to cut down on transportation costs, we would still be spreading single super phosphate all over the country. And if we did that at the rate that is recommended, and this would be the low rate that is recommended, at about 30 pounds per acre per year, we would be spreading 120 pounds of gypsum and that would be Florida gypsum full of radiation probably on every acre of agricultural soil, definitely east of the Mississippi and probably some distance west of the Mississippi. And we would have been doing that now for more than 100 years and we would have far exceeded the 2,700 pounds that the EPA has used and I venture to say right now that the EPA would not have had the temerity to ban single super phosphate.

Thank you, Mr. Chairman.

Mr. Putnam. Mr. Lloyd, your comments at this stage in the game?

Mr. Lloyd. I would like to correct one thing that was said. Ms. Cotsworth made the comment that the concentration was increased in phosphogypsum. The concentration of radioactivity is actually reduced in phosphogypsum.

I would like to receive the documentation that she had mentioned that says they had checked out building roads with 10 picocurie phosphogypsum. If that is in any of the BID documents, I cannot find it. Doug, were you ever able to find it, using 10 picocuries for road building?

Dr. Chambers. I did not see their analysis--I cannot recall seeing their analysis of 10 picocuries per gram.

Mr. Lloyd. So I would like to see that.

The one thing that might be interesting to you as a Congressman, in the 1989 rule, the public participation never discussed banning phosphogypsum. That part was not part of the discussion or the rule. And I would appreciate this easy-to-use guidance. We asked for it back in 1995. I would think 19 years is a long time to get it done.

Mr. Putnam. Ms. Cotsworth, could you provide to the subcommittee the background information, the studies on road building using to 10 picocurie per gram material for north Florida?

Ms. Cotsworth. Just a minor correction. I indicated that we did studies that suggested that a national generic permission for use as road building material was not supported in terms of risk. I do not believe I used the term 10 picocuries per gram in regard to that specific reference.

In the BID documents, as requested, the specific reference is to an investigator by the name of Roffler, Gamma radiation and radon flux from roads constructed with bases having phosphogypsum-bearing aggregate, from the University of Florida, 1987. And the information is contained, I believe, on pages 426 and 427. That is the information that the staff at that point used.

Mr. Putnam. Thank you.

The real crux of all this is that it is the opinion of--and I believe the adopted policy of at least this county that finding a viable economic use for these stacks is our goal. And the State of Florida has invested, through the Department of Education and with substantial support from the private sector, in the Florida Institute of Phosphate Research, as well as the other academic studies that have gone on, to find a use for this product.

I am hopeful that this hearing will have communicated to the EPA our interest in allowing research to go forward that would provide us some guidance for alternative use of this product. It has bubbled under the surface for years and has been something that people talk about when they drive down Highway 60 and they see them. But it has reached an important sense of urgency as a result of the events of last summer and the discharge that had to occur, that highlights the potential risk that storing these stacks poses. I think it is tragic that legitimate, accredited, highly thought of researchers have a difficult time interacting with their government and finding a way to share research that has the potential for public benefit. And that has transcended Republican administrations, Democrat administrations. It is a culture issue at EPA that has absolutely nothing to do with who is in charge, because the same people are in those offices in Atlanta and at the mid level and everything else that make these decisions.

So I would hope that as a result of this hearing, which may just be the second of several if need be, that we would facilitate a better information transfer, that we could have some objective, some goal line of knowing what the definition of a complete application is so that process can move forward and the people of Polk County, people of Florida and the potential new industries that could come from alternative uses and the potential savings that could accrue in terms of road building or land fill management would be able to have some guidance. And that guidance, that progress, has been lacking. And it has been, I think very frustrating for an awful lot of people.

So, you know, I would hope that we would get the information that we have requested, that we can facilitate the meetings that you have committed to and, frankly, I think expand it certainly to include my office and your water office, we will make that communication as well, because I think

something that has come forward today is that there clearly has to be a conflict of environmental goals between your water office and your air quality office when your water office is sent to respond to an emergency created by the concentration of phosphogypsum in stacks and the water that is held as a result of rainfall and everything else. So I think that is an important component to this as well. And I invite you to respond.

Ms. Cotsworth. I want to make this petition process work for both the agency and the petitioners. And I have made it a priority since I have become the office director to both clearly respond to and process the current petition that we have in-house, and to issue the guidance that petitioners have been crying for. I also believe that I personally have a reputation for being someone who deals honestly and openly and is accessible to members of the regulated community as well as the rest of the public. And I am interested in making sure that--the bottom line is that the decisions that we make are clear and transparent, but also publicly and technically and scientifically defensible.

So I will certainly be willing to work with your office and the other people at this table. I know science has progressed, there have been changes in the agency since 1989 and the 1992 regulations. There has also been culture changes within the agency. But I will be glad to work with the petitioners, your office, our fellow regulatory agencies and others in regard to this issue.

Mr. Putnam. Thank you very much.

How many other issues are in your portfolio that involve this type of history with a State-sponsored research laboratory who has been specifically charged with investigating the use of a product that you regulate and has that kind of 19-year tradition of trying to move this along. Is that a fairly common thing?

Ms. Cotsworth. No, it is fairly unique.

Mr. Putnam. In most agencies or departments, you would assume in life that when you have sort of a small universe of players and one of them has been around since day one and are legitimate, you know, they are not--you know, being in the constituent service business, we all understand that sometimes folks come to the table bearing more research and more facts and have the credentials to back those up. It would seem that a better relationship would have just naturally developed over time, knowing that there is a whole building out here full of laboratories working to do nothing but find a better use for phosphogypsum, and it just seems odd that it has degenerated into sort of an adversarial thing instead of really a committed partnership to find a better use.

I take you at your word and hope that today marks a turning point and a move toward progress toward working to resolve these issues.

I also just wanted to ask if there were, as part of the Clean Air Act reauthorization, if there were a legislative change that affected the regulation of phosphogypsum that would allow for the use in these instances--road beds and landfills as well as a couple of the other things that we talked about, the glass and the marine life--would you lay awake at night worried about public health and the impact that might have on the population?

Ms. Cotsworth. It is inappropriate for me to comment on the possibility of legislative changes. Again, we will be glad to work with you or whomever on the Hill in regard to technical evaluation, give you our best technical and scientific input for you to use in making your tough decisions relative to legislation and then we will implement them appropriately.

Mr. Putnam. Thank you.

Mr. Keaton, would you like to add anything?

Mr. Keaton. Well, I guess in listening to everything that has been said, I think one thing that maybe we ought to point out here is that the doses and the risks that we have been talking about are calculated. These are numbers and models that we use to work with. There is real risk involved with hazards with this material getting into the environment as far as a dam breaking or things along these lines. So there are risks there that have to be balanced and I guess the EPA and the people have to deal with that.

What we do, what we would welcome is that the unfettered research and development of these products and these techniques in using this material, we welcome them and would work to help do that.

Mr. Putnam. Thank you. Mr. Eckenrod.

Mr. Eckenrod. You may have heard me shudder a little bit at the discussion earlier about some of the potential marine uses of phosphogypsum. I think we do need to think very carefully, as we would about any potential uses on the environmental effects of those. But it looks to me like--and I go back to what Mike Lloyd said earlier--that in the past when FIPR has talked to EPA, it has been constructive, they have made progress. So to the extent that this hearing can help get that constructive dialog back on track, I think it will be very successful.

Mr. Putnam. Thank you very much. Mr. Lloyd. Dr. Sumner. Dr. Chambers.

Mr. Chambers. Just a very brief comment. I would like to correct something as well.

There was in fact a detailed radiological assessment submitted along with the petition and so someplace in EPA files, there is information on radioactivity and potential radiological risks associated with it.

Other than that, when we submitted these, we tried to write them in a form, we sat down and asked ourselves a question if we were EPA, what kind of information would we like. So it may not be quite right, but we did make an attempt to make it easy. So we are hoping that EPA considers the work that we did in submitting the application when they come up with their guidelines.

Thank you very much.

Mr. Putnam. Thank you. Dr. Shieh.

Mr. Shieh. I would like to make a final comment. It seems to me the whole process looks at the project as a full scale operation, but it is not. It is still just one study and the finding of that study will provide solutions for big scale application. So a lot of effort has been put to me, it seems not in the right direction--a lot of effort we are doing today may not be necessary. So I want to ask again, please do not treat this project as a full scale application request, this is just one study to demonstrate if this idea is feasible or not feasible.

Mr. Putnam. Especially the phase III request, right?

Mr. Shieh. Yes, yes, yes.

Mr. Putnam. Well, I want to thank all of our distinguished panelists for their contribution to our understanding of this issue and the potentially beneficial uses as well as the risks that have to be balanced in using phosphogypsum for purposes other than stacking. It is necessary to reconsider the calculations that determine the commercial product or waste, in my view. We have a number of studies that suggest that it would be advantageous to everyone as well as environmentally sustainable to revise the EPA ban of phosphogypsum in research and in industry.

Certainly as was the case in the event there are additional questions we did not have time for today, the record will remain open for 2 weeks for submitted questions and answers. I believe that the subcommittee has put forward a number of information requests that we expect to be answered promptly, and we certainly appreciate the efforts that everyone has put into this.

I would note also for the record that the Florida Institute of Phosphate Research is within walking distance of this facility and I suspect if we want to use this as an opportunity to put our panelists together, I believe Mr. Lloyd might answer this correctly--available for all of our panelists to huddle up and talk about exactly what some of the issues are and how we can resolve this and make the application complete and move forward in a thoughtful, science-based manner.

So with that, I want to thank the audience for attending as well, I think your interest certainly demonstrates community involvement and a community interest in seeing this move forward in a productive and fruitful way. And the subcommittee stands adjourned.

[Whereupon, at 1:19 p.m., the subcommittee was adjourned.]

[Additional information submitted for the hearing record follows:]

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Review article

Environmental impacts of phosphogypsum

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Abstract

Phosphogypsum is an acidic by-product from the phosphate fertilizer industry. Large quantities are produced world-wide and it is estimated that by the year 2000 up to 280 million tonnes will be produced annually. Although phosphogypsum is mainly calcium sulfate dihydrate, it contains elevated levels of impurities which originate primarily from the source phosphate rock used in P fertilizer production. The main environmental concerns associated with phosphogypsum are: (i) movement of fluoride, sulfate, total dissolved solids, certain trace elements, and radionuclides from the U-238 decay series below phosphogypsum stacks into groundwater supplies; (ii) radon-222 exhalation which may pose a health risk to workers on the site or people living close to stacks; (iii) acidity; and (iv) radon-222 exhalation from soil into residential homes when agricultural land previously treated with phosphogypsum is converted to residential usage. In order to fully understand the environmental impact of phosphogypsum, it is necessary to understand the geochemical and hydrological processes that control the composition of phosphogypsum leachates and the attenuation of environmentally sensitive chemical species when these leachates enter soil environments. This article will review the chemistry of phosphogypsum and the environmental concerns associated with phosphogypsum that is stockpiled in waste repositories or is used as an agricultural soil amendment.

Key words: By-product gypsum; Radon; Natural-occurring radioactivity; Heavy metals; Fluoride; Waste management

1. Introduction

Phosphogypsum is an acidic by-product produced by the phosphate fertilizer industry during the production of phosphoric acid from phosphate rock. The by-product is composed mainly of gypsum and the phosphorus content is usually below 1%. Levels of fluoride, certain natural-occurring radionuclides and trace elements are relatively high and there is concern that the material may pose a negative impact on the environment. World-wide production of phosphogypsum was 120–150 million metric tonnes in 1980 (Carmichael, 1988) and it is estimated that if historic trends continue, production will increase to 220–280 mmt by the year 2000 (Ferguson, 1988). A study in 1981 showed that of the phosphogypsum produced, 14% is reprocessed, 58% is stored and 28% is dumped into water bodies (Carmichael, 1988). The objective of this review is to summarize the literature dealing with phosphogypsum, with emphasis on the chemistry of phosphogypsum and

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the concerns which may arise when phosphogypsum leachates come in contact with the terrestrial environment.

Large amounts of phosphogypsum are dumped, often into water supplies throughout the world. The Djorf Lasfar plant in Morocco pumps 25 000 tons/day of phosphogypsum into the Atlantic Ocean when operating at nominal capacity (Becker, 1989). Readers interested in the environmental consequences of dumping into water should consult articles by Becker (1989) and van der Heijde et al. (1988, 1990). Readers should refer to other reviews (Arman and Seals, 1990; Novikov, 1990) for more information on the possible utilization of phosphogypsum in engineering and chemical industries.

2. Phosphoric acid production

Phosphoric acid, which is used in phosphate fertilizer production, can be produced either by: (i) the electric furnace process, which uses electrical energy to produce elemental P as a first stage; or (ii) the wet process using sulfuric acid attack. Currently, the wet process accounts for over 90% of phosphoric acid production (Becker, 1989). Phosphate rock, which is composed mainly of apatite, is treated with concentrated sulfuric acid and water to produce gypsum, phosphoric acid and hydrogen fluoride. The most common process results in the production of calcium sulfate dihydrate:

$$Ca_{10}(PO_4)_6F_2 + 10H_2SO_4 + 20H_2O \rightarrow 10CaSO_4 \cdot 2H_2O + 6H_3PO_4 + 2HF$$

Once crystallized, the gypsum is separated from the liquid phase by filtration, mixed with water and sluiced to a disposal area or a holding area. The acidic process water is recycled. Hydrofluoric acid reacts with undissolved silicate impurities in phosphate rock to produce silicon tetrafluoride (SiF_4), which hydrolyzes to form fluorosilicic acid (H_2SiF_6). High temperatures produced during processing may allow the F acids to decompose forming gaseous SiF_4 and HF. These are usually recovered as fluorosilicic acid (H_2SiF_6) by absorption in water using scrubbers.

Phosphate rock is usually treated in a physical process called beneficiation, prior to acid treatment in order to concentrate the P content of the ore (Becker, 1989). Beneficiation often involves concentration by washing, screening and flotation (Roessler, 1979a). Calcination, the crushing of rock and heating to 910°C, may be required to reduce the organic content down to approximately 1% prior to acidulation (Norris, 1969; McClellan and Gremillion, 1980).

Approximately 5 tonnes of phosphogypsum are produced per tonne of phosphoric acid (P_2O_5). The degree of calcium sulfate hydration depends on the operating acid concentration and temperature (Witkamp and van Rosmalen, 1986), and may increase during transport and storage of the phosphogypsum. The dihydrate ($CaSO_4 \cdot 2H_2O$) phosphoric acid process, which is the most common (Yarnell, 1987), produces 28–30% acid. The hemihydrate process ($CaSO_4 \cdot 0.5H_2O$), relatively widely used in Europe, Japan and Africa, produces a purer phosphoric acid product with higher P_2O_5 concentration (Kouloheris, 1980). Various modifications to the hemihydrate process have been adopted by companies to produce acid concentrations between 32 and 52%. Details of various wet phosphoric acid processes are summarized by Becker (1989) and Kouloheris (1980).

2.1. Chemical and mineralogical composition of phosphate rock

Phosphate ore partly determines the nature of the phosphorus fertilizer and phosphogypsum. Phosphate ores are of sedimentary, or of igneous and metamorphic origin. Sedimentary phosphates, also known as phosphorites, represent about 85% of known phosphate rock (Habashi, 1980). The most easily mined deposits are from the great sedimentary basins which formed approximately 70 million years ago and are associated with matter from living organisms (Becker, 1989). Phosphate ores are subject to wide compositional variation and differences in quality. Apatite is the principle phosphate mineral in most phosphate deposits (Lehr and McClellan, 1972). Becker (1989) presents the chemical composition of phosphate rock concentrates from a variety of sources. Major components are CaO (29–54%), P_2O_5 (24–40%),

SiO_2 (0.1–14%), F (1.3–4.1%), CO_2 (0.2–7.3%), SO_3 (0.0–3.3%), Al_2O_3 (0.2–1.8%), Fe_2O_3 (0.1–2.6%), MgO (0.0–2.2%) and Na_2O (0.2–1.5%). Phosphorites contain approximately 10% quartz, 5% muscovite-illite, 2% organic matter, 1% dolomite-calcite, 1% iron oxide, and 1% other components (Gulbrandsen, 1967). The most common Fe-Al oxides and hydroxides identified in sedimentary phosphate rock are goethite, limonite, bauxite minerals and barbosalite (McClellan and Gremillion, 1980). Minor components include fluorite, zircon, tourmaline, montmorillonite, kaolinite, sphene and pyrite (Gulbrandsen, 1967). Other accessory minerals include titanium minerals such as rutile, ilmenite, anatase and perovskite (McClellan and Gremillion, 1980).

Francolite is the amorphous form of apatite in sedimentary phosphorites. Igneous fluorapatite has the formula $Ca_5(PO_4)_3F$ but francolite exhibits more elemental substitutions (Osmond et al., 1985; McClellan and Lehr, 1969). Apatite varies greatly in physical, chemical and crystal properties (Lehr and McClellan, 1972). The most common apatites are carbonate apatites with isomorphous substitution of carbonate and F (CO_3F groups) for phosphate and minor substitution of Ca with Na and Mg atoms (McClellan and Lehr, 1969; Lindsay et al., 1989).

The enrichment of trace elements in phosphorites is best compared relative to shale, a common marine rock and the most common surficial rock (Altschuler, 1980). Compared to shale, the trace elements enriched in the average phosphorite are Cd (60×), U (30×), Ag (30×), Y (10×), Se (8×), Yb (5×), Mo (4×), La (4×) and Sr, Pb and Zn (each 2×). The rare earth elements, except for Ce, also exhibit enrichment relative to shale (Altschuler, 1980). The elements depleted are Li (13×), Ti (7×), Hg (7×), B (6×), Ga (5×), Co (3×) and Sn and Zr (each 2×) (Altschuler, 1980). Tooms et al. (1969) compared the elemental composition of phosphates from a variety of sources and concluded that relative to average crustal abundances, As, Cr, and Sn were enriched and Ba, Cu, Mn and Ni were depleted. Gold and Th concentrations appear to be similar in phosphorites relative to shales and Bi is enriched (Altschuler, 1980). Enrichment of Bi may be due to substitution in apatite because the ionic radius of the Bi^{3+} ion (0.093 nm) is close to Ca^{2+} (0.099 nm) (Altschuler, 1980).

Enrichments vary between phosphorite formations. For example, relative to shale the following trace elements are enriched in the Phosphoria formation: Ag (60×), Mo (50×), Se (20×), Nd (10×), Cr (10×), As (4×), Cu (2×) and V (2×). The following elements are depleted: Zr (6×), Mn (30×), Ba (6×) and Pb (2×) (Gulbrandsen, 1966).

Some of the elements enriched in phosphorites are known, or are theorized on crystallographic spacings, to substitute for Ca in apatite. These elements are Cd, U, Sr, Pb, Zn, Y and the lanthanides (Altschuler, 1980). Substitutions of Na^+ for Ca^{2+} and SiO_4^{4-} for PO_4^{3-} maintain electrical neutrality. Small quantities of CO_3^{2-}, VO_4^{3-}, AsO_4^{3-} and SO_4^{2-} may substitute for PO_4^{3-} in the crystal structure (Sweeney and Windham, 1979). Silver, Se and Mo are often associated with organic matter and enrichment may be due to complexation or adsorption with organic materials, similar to reactions found for As, Cd, Cu, Ni, Sb, V and Zn (Krauskopf, 1955; Gulbrandsen, 1966), or as metallic sulfide precipitates formed under reduced conditions (Altschuler, 1980). The elements depleted in phosphorite usually either occur in relatively stable and insoluble minerals, or they possess cationic or anionic configurations which cannot fit into the apatite crystal structure.

2.2. Natural radioactivity in phosphate rock

Many phosphate ores are high in natural radioactivity relative to shale. The radioactivity originates mainly from the U-238 and Th-232 decay series (see Figs. 1 and 2) and varies with the type of phosphate rock. Uranium-235 is not as prevalent in nature as U-238 and consequently radiation originating from this decay series is not considered to be a concern. Sedimentary phosphates typically contain high U concentration and low Th concentration, but igneous phosphates typically contain low concentrations of U and an appreciable amount of Th and rare earth elements (Habashi, 1980). Radionuclide concentration in the beneficiated rock is typically 100–300% of the concentration of the unprocessed rock (Roessler 1979a). Metzger et al. (1980) reported that the specific activities of U and Th-230, and the con-

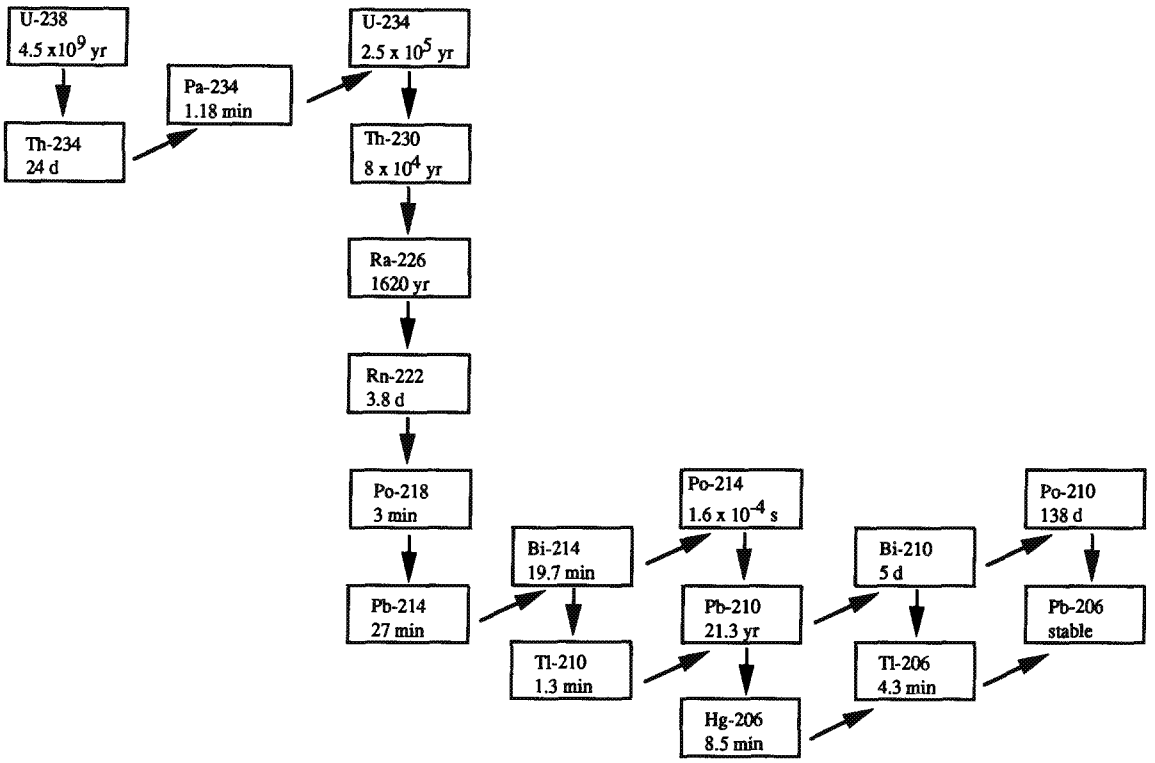

Fig. 1. Uranium-238 decay series. Diagonal arrows designate beta-decay and vertical arrows designate alpha-decay. Radionuclide half-lives are included.

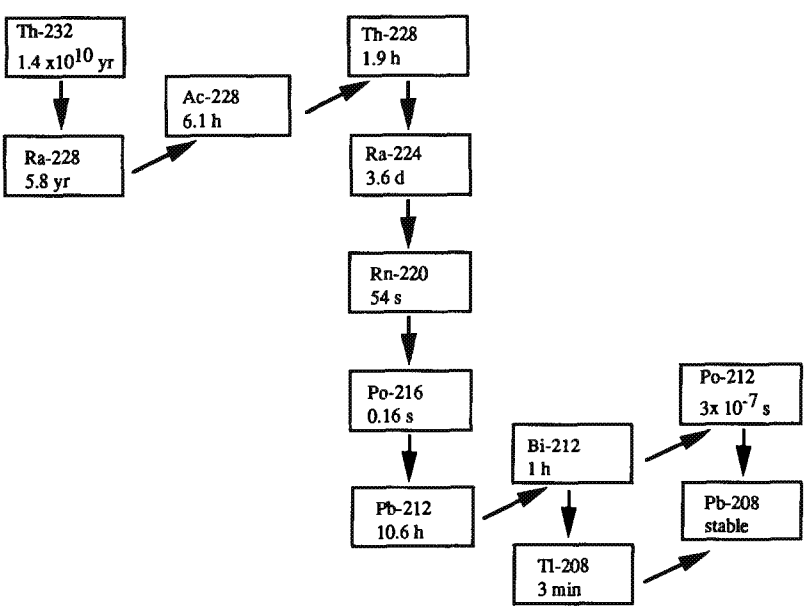

Fig. 2. Thorium-232 decay series. Diagonal arrows designate beta-decay and vertical arrows designate alpha-decay. Radionuclide half-lives are included.

centrations of Al, Cu, Mg, Na, Ti and Zn, were found to increase with decreasing particle size of beneficiated ore.

Uranium commonly exists in two oxidation states, U(IV) and U(VI). Most researchers agree that U as U(IV) replaces Ca in the apatite structure; however, some U(VI) may be adsorbed as the uranyl ion (UO_2^{2+}) onto apatite crystal surfaces (Hurst and Arnold, 1980; Burnett et al., 1988). Uranium (IV) may also be adsorbed or exist as a chemically-complexed phase on clay minerals and organics (Upchurch et al., 1991). In Florida phosphate rocks, U(IV) represents 40–90% of the 10–200 $\mu g\ g^{-1}$ of U (Lindeken, 1980). Menzel (1968) summarized the contents of U, Ra and Th in phosphate rocks from different sources around the world. Uranium content ranged from 3 $\mu g\ g^{-1}$ in ore from Chile and Ecuador islands to 399 $\mu g\ g^{-1}$ in ore from South Carolina. Typical soil values for U are approximately 2.7 $\mu g\ g^{-1}$ (Sposito, 1989).

Thorium exists in the +4 state in nature. Thorium (IV) probably substitutes for Ca in the apatite structure due to the similarity of the two ionic radii (IR = 0.102 vs. IR = 0.099 nm, respectively), although thorium may also concentrate in other compounds because it readily coprecipitates with oxidate minerals like Fe and Mn oxides. Levels of radionuclides from the Th-232 decay series are usually low in most sedimentary phosphate ores (Metzger et al., 1980).

Radium-226 is the most abundant Ra isotope in sedimentary phosphate ores. Radium-228 is present at very low concentrations because it is a product of the Th-232 decay series (Osmond et al., 1985). Menzel (1968) found Ra levels to range from undetectable in western European phosphates to $133 \times 10^{-6}\ \mu g\ g^{-1}$ ore from South Carolina. Roessler et al. (1979a) found U-238 and Ra-226 activities in Florida phosphate ore to be in approximate secular equilibrium and averaged 0.3 Bq g^{-1} in north Florida and 1.4 Bq g^{-1} in central Florida. Due to the chemical and crystallophysical properties of Ra-226 the radionuclide probably does not occupy regular lattice positions within U-bearing materials (Burnett et al., 1988). Where as U(IV) (IR = 0.097 nm) often substitutes for Ca (IR = 0.099 nm) in apatite due to the similarity of size (Hurst and Arnold, 1980), Ra has an ionic radius of approximately 0.152 nm (Ames and Rai, 1978; Vdovenko and Dubasov, 1975), which is too large for the isomorphous replacement of Ca. Likely, Ra in phosphorite is co-precipitated with Ba and/or Sr as a sulfate compound.

A review of world-wide data on natural radioactivity in phosphate rock, products and by-products was presented in the 1977 report on the United Nations Scientific Committee of the Effects of Atomic Radiation (UNSCEAR, 1977). Guimond (1978) also reviewed the natural radioactivity associated with the phosphate industry.

3. Characteristics of phosphogypsum

3.1. Physical characteristics

Phosphogypsum has physical properties similar to natural gypsum. Particle density ranges between 2.27 and 2.40 g cm^{-3} (SENES, 1987). Bulk density within phosphogypsum stacks has been reported to range between 0.9 and 1.7 g cm^{-3} (Vick, 1977; Keren and Shainberg, 1981; May and Sweeney, 1984a). Phosphogypsum generally has a large proportion of medium to fine-grained particles. May and Sweeney (1984a) reported medium sized particles (0.250–0.045 mm diameter) to account for 36–60% of the mass of seven phosphogypsum samples. Fine particles (<0.045 mm diameter) accounted for 2–49% of the mass. SENES (1987) reported 30% of the phosphogypsum obtained from a stack in Dunnville, Ontario to be of fine size or smaller, while 50% of the phosphogypsum was of fine size or smaller at another stack at Calgary, Alberta. The fine particle size of phosphogypsum results in a rapid dissolution rate relative to mined, natural gypsum (Keren and Shainberg, 1981). Harvie et al. (1984) estimated the solubility product for gypsum to be 2.63×10^{-5} at 25°C. Vertical hydraulic conductivity of phosphogypsum has been reported to range between 1×10^{-3} and 2×10^{-5} cm s^{-1} (SENES, 1987).

The free water content of phosphogypsum may vary greatly depending on how long the phosphogypsum has been allowed to drain after sluicing to the stack, and on local meterological conditions. The free water content of phosphogypsum is often

determined by drying at 65°C for 5 h. This method may result in the loss of some water of hydration when drying occurs above 60°C. Drying at a lower temperature may be very time consuming; consequently Averitt and Gliksman (1990) recommend drying at 50°C for 5 h under vacuum.

Phosphoric acid process conditions influence the crystal morphology of phosphogypsum. It is important that the gypsum crystals produced do not have surface-to-volume ratios which are so high that they impede phosphoric acid flow during filtration (Becker, 1989). Crystal shape and size distribution determine the surface-to-volume ratio and filter cake porosity (Becker, 1989). Common gypsum shapes include needles, small thin lozenges, rhombic and X-shaped swallowtail twins, flat table-like, clusters and thick rhombic types (Becker, 1989). Ball-like clusters have the minimal surface-to-volume ratio and produce the most rapid acid flow rates. The most common shape is a table-like elongated crystal, with dimension ratios of 16:4:1 (Becker, 1989). May and Sweeney (1984a) reported that Florida phosphogypsum exhibited monoclinic crystals which were tabular and diamond-shaped. This was also found by Luther et al. 1993. Larger crystals had sides ranging between 15 and 30 μm, a thickness of 3–5 μm and a length of 20–40 μm. Solid needle shapes, hollow four-sided tubular shapes and thin flakes were also observed.

The factors which control the shape and size of the gypsum crystals formed in the reaction slurry are: (1) the type of phosphate rock; (2) phosphate rock particle size; (3) concentration of phosphoric acid; (4) solids content in the slurry; (5) excess sulfuric acid in the slurry; (6) impurities in the phosphate rock; (7) temperature; and (8) the reaction system, feed-to-volume ratios, agitation, and recirculation (Becker, 1989).

3.2. Chemical and mineralogical composition

The chemical and mineralogical characteristics of phosphogypsum depend on the nature of the phosphate ore, the type of wet process used, the efficiency of plant operation, the age of the stockpile, and any contaminants which may be introduced into the phosphogypsum at the production plant (Arman and Seals, 1990). Calcium and SO_4^{-2} dominate the composition of phosphogypsum because it is approximately >90% gypsum (Berish, 1990). Phosphogypsum is acidic due to residual phosphoric acid, sulfuric acid and fluoride acids contained within the porosity. May and Sweeney (1984a) found the pH of extracts from Florida phosphogypsum to range between 2.1 and 5.5. The pH of aged and leached phosphogypsum may approach neutrality (SENES, 1987). The acidic nature of fresh phosphogypsum may keep trace elements dissolved from phosphate rock in a potentially mobile state.

Although phosphogypsum solids are mainly gypsum, many impurities are present. These include quartz, fluorides, phosphates, organic matter and minerals of Al and Fe. Using X-ray diffraction, May and Sweeney (1984a) found α-quartz to make up approximately 5% of Florida phosphogypsum. May and Sweeney (1984b) conducted X-ray analyses on the evaporites of water-soluble material from gypsum and found only gypsum and hemihydrate. The sensitivity of the analysis was not sufficient to identify trace element compounds. Luther et al. (1993) found crystalline or amorphous materials among the matrix of well-formed gypsum crystals using SEM-EDX. These minerals were dominated by Si and/or P, combined in some cases with significant amounts of Al, Na, K, Ca and/or S. The Si was attributed to α-quartz, or to feldspars in the presence of Al and Na or K. The P was attributed to residual phosphate rock. Some samples contained as much as 10% SiO_2 and 1.6% P_2O_5. Silica is sometimes added to the liquor in phosphoric acid production to assist in the crystallization process (Beretka, 1990). Silica may also originate from sand present in process water supplies.

Major elemental composition of phosphogypsum varies according to the type of wet phosphoric acid process used (Table 1). Minor element composition may vary greatly depending on the source of the phosphate rock (Table 2). Luther et al. (1993), in part, studied the elemental composition of Alberta phosphogypsum originating from western Idaho rock and compared the results with literature values for terrestrial materials (Table 2 and 3). Relative to shale, phosphogypsum was elevated in total content of Ag, Au, Cd, Se, Sr, and some of the light rare earth elements and Y. Phospho-

Table 1
Typical major element composition (%) for phosphogypsum produced under different processes[a]

Component	Dihydrate	Hemihydrate	Hemi-dihydrate
CaO	32.5	36.9	32.2
SO_3	44.0	50.3	46.5
P_2O_5	0.65	1.50	0.25
F	1.2	0.8	0.5
SiO_2	0.5	0.7	0.4
Fe_2O_3	0.1	0.1	0.05
Al_2O_3	0.1	0.3	0.3
MgO	0.1	—	—
H_2O (Crystalline)	19.0	9.0	20.0

[a]Adapted from Kouloheris, 1980.

Table 2
Content (mg kg^{-1}) of some trace elements in phosphogypsum (PG) produced from different rock phosphate sources[a]; also included are literature values for terrestrial materials

Element	Florida source PG	Idaho source PG	South African source PG	Tunisian source PG	Shale[b]	Typical soil[c]
Ag	<1	1–11			0.1	0.05
As	40	<1–2			10	7.2
Au ($\mu g\ kg^{-1}$)		3–15			3	
B	3	<10–30			100	33
Ba	7	20–140	140		600	580
Be	1	1–2			3	0.92
Br		1–2			5	0.85
Cd	7	9–28		40	0.3	0.35
Cl		<100–300			170	100
Co	2	<1–1		8	20	9.1
Cr		<10–70			100	54
Cu	8	10–42	103	6	50	25
Hg ($\mu g\ kg^{-1}$)			<50	14000	300	90
Mn	15	<2–10			850	550
Mo	16	<1–2		5	2	0.97
Ni	2	3–15	13	15	80	19
Pb	1	3–7			20	19
Rb		<10–20			140	67
Sb	100	0.3–0.8			1.5	0.66
Se		4–67			0.6	0.39
Sr	10	610–670			400	240
Th		<1–1			12	9.4
U		6–13			3.5	2.7
V	19	10–40			130	80
Y	2	100–120	50		35	25
Zn	9	18–112	6	315	90	60
Zr	10	<10–110	185		170	230

[a]Florida source phosphogypsum from May and Sweeney (1984a); Idaho source phosphogypsum from Luther, et al. (1993); South African source phosphogypsum from Malan (1988); Tunisian source PG from Rouis and Bensalah (1990).
[b]From Krauskopf (1979).
[c]From Sposito (1989).

Table 3
Content (mg kg^{-1}) of selected rare earth elements in dihydrate phosphogypsum produced from Idaho phosphate rock[a] and literature values for terrestrial materials

Element (Z)[b]	Idaho		Shale[c]	Soil[d]
	Mean	Range		
La (57)	81	69–90	40	37
Ce (58)	36	31–45	70	49
Nd (60)	36	30–46	30	46
Sm (62)	5.4	4.7–6.3	7	6.1
Eu (63)	1.2	1.1–1.4	1.4	1.9
Tb (65)	1	0.8–1.2	1	0.63
Yb (70)	2.8	2.6–3.5	3.5	2.3
Lu (71)	0.41	0.36–0.51	0.6	0.34

[a]From Luther et al. (1993).
[b]Atomic number.
[c]From Krauskopf (1979).
[d]From Sposito (1989).

gypsum from central Florida had greater As, Sb and Mo content than the Alberta phosphogypsum but had lower concentrations of Ag, Ba, Cd and Sr. In terms of total concentrations, May and Sweeney (1984a) said phosphogypsum could not be classified as a toxic waste because it was neither corrosive (pH was >2 and <12.5) and because the average total elemental concentration of elements classified as toxic by the E.P.A. (As, Ba, Cd, Cr, Pb, Hg, Se, and Ag) were less than the E.P.A. allowable toxic elemental criteria for toxic hazardous waste (Federal Register, 1980).

Levels of Y, Zr, Cu, Ba, and Ni in South African phosphogypsum were much greater than central Florida levels (Table 2). Tunisian phosphogypsum was reported to contain very high levels of Cd, Hg and Zn. Compared to Quebec standards for the classification of contaminated soil, the phosphogypsum was slightly contaminated with Zn and Mo, but highly contaminated with Cd and Hg (Rouis and Bensalah, 1990).

Table 4
Trace element transfer (%) from U.S. phosphate rock into phosphogypsum[a]

Element	Percent transfer
Cd	30–54
Cu	64–100
Zn	20–49
Cr	3–26
V	1–100

[a]Adapted from Becker (1989).

Berish (1990) identified acidic process water, fluoride, radionuclides and heavy metals as possible contaminants of concern in phosphogypsum. Table 4 shows the percent transfer of trace elements from phosphate rock to phosphogypsum during the wet phosphoric acid process. Although the dihydrate process has the advantages of lower capital outlay, lower production costs, the ability of processing varying grades of phosphate rock and the capability of producing an acid from which U can be extracted (Kouloheris, 1980), the process has the major disadvantage of producing a gypsum with the most impurities. The impurities are mainly fluorine compounds (1.5–2.5%) and phosphate compounds (0.82% by wt.) (Schroeder and Gorecki, 1980). Filter cakes from the dihydrate process may contain as much as 0.5–1.0% P_2O_5. Impurities in typical hemihydrate are still relatively high and there is no method to extract U from the acid of this process (Kouloheris, 1980). The hemi-dihydrate process produces a relatively clean phosphogypsum filter cake (Table 1).

The form of major and trace elements in a solid can be attributed to a number of processes including precipitation in an essentially pure mineral

phase, fluid inclusions, co-precipitation, solid solution formation and adsorption on the surface of organic or mineral components (Luther and Dudas, 1993). Free phosphoric acid, unreacted phosphates, sodium hexafluorosilicate, sodium sulfate, fluorosilicic acid and organic compounds may adhere to the surface of gypsum crystals. Elements which substitute into the gypsum structure include Cd (van der Sluis et al., 1986; Witkamp and van Rosmalen, 1988), Sr, Mg, Na, K and Cl (Kushnir, 1980) and Se (Neal, 1990). Dicalcium phosphate, monosodium sulfate and fluorophosphates may also substitute into the crystal structure of gypsum crystals. Fluorite and fluorapatite may be the potential solubility controlling solids for F in phosphogypsum (Murray and Lewis, 1985; Jenne et al., 1980). A solid solution exists between gypsum and dicalcium phosphate because HPO_4^{2-} ions replace SO_4^{2-} ions in the gypsum lattice structure (Goers, 1980; Olmez and Erdem, 1989). Substitution of phosphate into the gypsum crystal during acidulation is reduced with higher SO_4^{2-} concentrations, longer phosphate attack times, higher reaction temperatures and high percent solids (Goers, 1980). Silicon probably exists as amorphous SiO_2, quartz or in SiO_2-containing minerals (Lindsay, 1979; Rai et al., 1987).

Fluorapatite contains up to 1% by mass of rare earth elements (REE) (Berdonosova et al., 1989). Phosphogypsum may be composed of 0.5% lanthanide oxides (Kijkowska et al., 1989). The REE are members of Group IIIA in the periodic table and are also referred to as the lanthanide series. They have similar chemical properties because all have a relatively stable +3 oxidation state. Yttrium is not a REE but it shares a similar chemistry with REE and is therefore often discussed with members of the REE (Henderson, 1984). Sixty to 80% of the REE present in phosphate rock may be partitioned into the phosphogypsum (dihydrate or hemihydrate) during the production of phosphoric acid (Andrianov et al., 1976; Berdonosova et al., 1989). However, there is evidence that heavy REE (Gd to Lu) may be preferentially partitioned into phosphoric acid compared to the light REE (La to Sm) during the wet phosphoric acid process (May and Sweeney, 1984b). Elements such as Ce^{3+} in the presence of Na^+ form a solid solution with hemihydrate during crystallization [$NaCe(SO_4)_2 \cdot H_2O + CePO_4 \cdot 0.5H_2O$] – $CaSO_4 \cdot 0.5H_2O$ (Bushuev et al., 1988). This stabilizes the hemihydrate sulfate structure and slows down the recrystallization of dihydrate sulfate during the hemi-dihydrate process (Bushuev et al., 1988).

It is not known what chemical forms many of the trace elements take in phosphogypsum, although sulfate and phosphate minerals are likely under aerobic, acidic conditions (Luther and Dudas, 1993). Possible solubility controlling solids for trace elements in phosphogypsum will be discussed in a later section.

3.3. Radionuclides and their geochemistry

Phosphogypsum is enriched in radioactivity relative to most geological and soil materials because it is derived from phosphate rock, which contains relatively high levels of naturally-occurring radionuclides. The source of radioactivity comes from two decay series originating from the two parent radionuclides, U-238 and Th-232 (Figs. 1 and 2). The U-235 or Actinium decay series also exists in nature but the shorter half-life of U-235 (7.13×10^8 years), compared to U-238 (4.51×10^9 years) and Th-232 (1.39×10^{10} years), has reduced the abundance of this U isotope over the millennia to 0.72% of total U. Thorium content in sedimentary phosphate ores is usually low (Menzel, 1968; Metzger et al., 1980) and is not considered an environmental concern except in igneous phosphate rock deposits.

In undisturbed natural deposits, the members of the U-238 decay series are in approximate radioactive equilibrium; however, some Rn-222 gas may diffuse out of the material, thereby reducing the activity of radionuclides which follow Rn-222 in the decay series. Beneficiation is a physical process which does not appreciably disrupt radioactive equilibrium but increases the radioactivity of the concentrated rock by up to 400% over the non-processed matrix (Roessler et al. 1979a; Lisachenko et al., 1987). During the wet phosphoric acid process, the radioactive equilibrium within the phosphate rock is disrupted and the radionuclides are partitioned into various phases according to their solubility (Roessler et al., 1979a; Lardinoye

et al., 1982). Uranium, Th and Pb-210 distribute primarily into the phosphoric acid while most of the Ra-226 and Po-210 partition into the phosphogypsum. Hurst and Arnold (1982) reported that 60% of the Ra-226 and 99% of the Po-210 appear in the gypsum.

Reported radionuclide activities in phosphogypsum are presented in Table 5. Radium-226 activity is usually the largest source of radioactivity in phosphogypsum although some authors have also reported high activities of U-234, U-238 and Po-210. The highest Ra-226 activities have been

Table 5
Summary of reported radionuclide activities in phosphogypsum

Location of phosphogypsum	Phosphate rock origin	Radionuclide	Mean activity (Bq kg^{-1})	Reference
Alberta	Idaho	Ra-226	890	Luther et al., 1993
		Th-228	5.8	Luther et al., 1993
Australia	numerous	Ra-226	500	Beretka, 1990
			451	Beretka and Mathew, 1985
		U-238	510	Beretka, 1990
		Th-232	10	
			10	Beretka et al,1985
		K-40	20	Beretka, 1990
Florida	central Florida	Ra-226	1140 (844–1670)[a]	Guidry, 1990
			1100 (836–1230)	Horton et al., 1988[b]
			820 (340–2000)	May and Sweeney, 1984b
			958 (780–1290)	Roessler et al., 1979a
		U-234	130 (100–180)	Horton et al., 1988[b]
			75	May and Sweeney, 1984a
		U-235	6	
		U-238	130 (93–190)	Horton et al., 1988[b]
			76	May and Sweeney, 1984a
		Th-227	21	
		Th-228	1	
		Th-230	113	
			190 (110–250)	Horton et al., 1988[b]
		Th-232	3.7	May and Sweeney, 1984a
		Po-210	1030 (984–1090)	Horton et al., 1988[b]
			1480[c]	Roessler et al., 1986
		Pb-210	1370 (1270–1430)	Horton et al., 1988[b]
	north Florida	Ra-226	500 (477–548)	Roessler et al., 1979a
		U-238	<20	
Hungary	Syria	Ra-226[d]	1093	Fourati and Faludi, 1988
		Ra-228[d]	68	
Louisiana	not given	Ra-226	1100 (700–1700)	Laiche and Scott, 1991
Mississippi	not given	Ra-226	780	Mullins and Mitchell, 1990
		Po-210	8.1	
Sweden	Kola (USSR)	Ra-226	15	NEA, 1979
		Th-232	62	
		K-40	48	
Yugoslavia	not given	Ra-226	390	Kobal et al., 1990

[a]Range.
[b]Active stacks only.
[c]Estimated assuming Ra-226 and Po-210 in phosphate rock were in equilibrium and 99% of Po-210 was partitioned into phosphogypsum during chemical processing.
[d]Estimated assuming equilibrium between Ra-226 and Bi-214, and between Ra-228 and Ac-228.

reported in phosphogypsum originating from central Florida rock, although phosphogypsum originating from Idaho or Syrian rock may be high as well. Generally, Th radionuclides have lower specific activities than Ra-226. Phosphogypsum produced from igneous rock phosphate may have Th-232 activities which exceed those of Ra-226.

Radium-226 content in phosphogypsum exceeds levels found in fly ash and soils, however, Th-228 content is generally less in phosphogypsum than fly ash or soil. Fly ash samples from coal combustion contain approximately 100 Bq kg^{-1} of Ra-226 (Coles et al., 1978; Kobal et al., 1990). Soil Ra-226 activity is typically less than 50 Bq kg^{-1} (Myrick et al., 1983; Kiss et al., 1988; Berish, 1990), although soil formed on high U containing parent materials may be more than 50-fold greater than this (Michel, 1987). Coles et al. (1978) reported Th-228 in fly ash to be 6–20 Bq kg^{-1}. Kiss et al. (1988) determined Th-232 and its daughter radionuclides to have an activity of 24 Bq kg^{-1} in Saskatchewan soils.

The specific activity of various radionuclides in phosphogypsum has been well reported; however, radionuclide geochemistry in phosphogypsum has not received much attention. The geochemistry of the radionuclides present in geological materials such as phosphate rock has been summarized in several publications (Ames and Rai, 1978; Osmond et al., 1985; Burnett et al., 1988; Upchurch et al., 1991).

Natural radioactive decay can affect the chemical behavior of radionuclides. For example, alpha recoil can break chemical bonds, move the recoiled atom to a different position in a solid and may damage crystal structures (Michel, 1987). This may have an effect on the activity of solids, especially ones of colloidal size, resulting in activities which exceed one (Upchurch et al., 1991). Biological processes can have an effect on radionuclide behavior. Birch and Bachofen (1990) review the effect of microbiologically derived complexing agents on radionuclide mobility. Microbially produced organic compounds have been found to increase the solubility of some radionuclides, such as U.

Uranium. The three naturally occurring isotopes U-234, U-235 and U-238 have average percent abundances of 0.0056, 0.72 and 99.27%, respectively, in the environment (Ames and Rai, 1978). The element is polyvalent and has complex solubility relationships depending on redox potential. Common oxidation states are +3, +4, +5 and +6, although the +4 and +6 states are the most stable (Ames and Rai, 1978).

Small amounts of U are normally contained within phosphogypsum. Most U from phosphate rock is partitioned into the phosphoric acid during the acidulation process (Roessler et al., 1979a; Hurst and Arnold, 1980); however, the partitioning is affected by redox conditions and the presence of other ions. Organic compounds in the processed phosphate rock tend to increase the U content of phosphogypsum (Gorecka and Gorecki, 1984). Uranium dissolution from phosphate rock is greater when acidulation is carried out under oxidizing conditions. Losses to the gypsum filter cake occur when unreacted rock particles are coated with gypsum or when U is substituted into the crystal lattice of the gypsum (Hurst and Arnold, 1980). Excess sulfate and fluoride may enhance the partitioning of U into the gypsum crystal. The U(IV) present in the crystal lattice of the apatite, and that formed by reduction of U(VI) by Fe(II) during acidulation, is trapped within the crystal lattice of the calcium sulfate crystals as they grow (Hurst and Arnold, 1980) because U(IV) and Ca^{2+} have very similar ionic radii (0.097 and 0.099 nm, respectively) (Gorecka and Gorecki, 1984). Thus, the presence of a large amount of Fe^{2+} may result in the transfer of as much as 80% of the U from the phosphate rock into the phosphogypsum. Uranium tends to concentrate in very small phosphogypsum particles (Gorecka and Gorecki, 1984). Under reduced conditions there is a greater transfer of U to phosphogypsum during processing. In contrast, 90–95% of U remains in the liquid phase under oxidizing conditions and in the presence of HNO_3. Small amounts of U may be present in phosphogypsum in the form of uranyl ion (UO_2^{2+}) contained within the residual phosphoric acid which remains after filtration and sluicing to the stack. Uranium (VI) may adsorb on the surface of gypsum as UO_2HPO_4 or UO_2^{2+} may substitute for two Ca^{2+} ions on the surface of the crystal lattice (Gorecka and Gorecki, 1984).

The U content of phosphogypsum also depends on the type of wet phosphoric acid process used. The dihydrate method results in a U content of 5–25 $\mu g\ g^{-1}$ but the hemihydrate process results in a content of 5–100 $\mu g\ g^{-1}$. This difference is due to several factors. The hemihydrate has a hexagonal instead of a monoclinic unit cell structure (Turk and Bounini, 1984) and forms agglomerates and clusters which more easily accommodate U into the crystal structure (Gorecka and Gorecki, 1984). Higher temperatures and higher phosphate concentration also favor coordination into the hemihydrate.

The chemical behavior of U is affected by pH and redox conditions. Under reduced conditions and pH below 3–4, the uranous (U^{4+}) ion forms complexes with fluoride. At higher pH, uranous-hydroxy complexes form. The solubility of U(IV) species are low, but U(VI) species may be quite soluble and mobile. At pH below 5 uranyl ion (UO_2^{2+}) and uranyl fluoride dominate. Between pH 4 and 7.5 $UO_2(HPO_4)_2^{2+}$ becomes prevalent. Uranyl di- and tri-carbonate species become prevalent at higher pH. Minimum solubility of uranyl minerals occurs between pH 5 and 8.5 and sorption occurs in decreasing order to organics, ferric hydroxides, Mn- and Ti-oxyhydroxides, and clays (Osmond et al., 1985; Upchurch et al., 1991).

The distribution of U radioisotopes in the environment is affected by the radioactive decay process. As U-238 forms Th-234 alpha recoil results in some of the daughter Th-234 atoms to be ejected from the mineral crystals into pore water or air. Thus this leads to a greater enrichment of U-234, the decay daughter of Th-234, in groundwater relative to U-238 (Upchurch et al., 1991).

Radium. Radium-226 is a major source of radioactivity in phosphogypsum. This radionuclide is formed by alpha decay of Th-230 within the U-238 decay series. Radium-228 is the second most abundant Ra isotope but it is quite rare in phosphogypsum because it is formed within the Th-232 decay series which is not abundant in marine sediments.

Radium belongs to the alkaline earth elements and therefore is divalent and has similar properties to Ca, Sr and Ba. Consequently, Ra-226 is an environmental concern because it follows similar biological pathways as Ca (Roessler, 1980). Between 70 and 90% of the Ra in the body is contained within bone (UNSCEAR, 1977).

Ra-226 probably does not co-crystallize with calcium sulfate dihydrate during phosphoric acid production because: (i) radium sulfate is very insoluble compared to calcium sulfate dihydrate, therefore almost all radium sulfate will be precipitated before the gypsum begins to precipitate; (ii) the ionic radii of Ra (IR = 0.152 nm) and Ca (IR = 0.099 nm) are so different that isomorphous substitution is unlikely; and (iii) radium sulfate (along with barium sulfate) crystallize in the rhombohedral system while calcium sulfate dihydrate crystallizes in the monoclinic system. There is a greater chance of co-precipitation of Ra-226 in the calcium sulfate hemihydrate system than with the dihydrate system because the former crystallizes in a rhombohedric system (Moisset, 1980). May and Sweeney (1984a), Beretka and Mathew (1985) and Moisset (1990) have reported that most Ra-226 in phosphogypsum is associated with fine phosphogypsum grains. The fact that Ra-226 is more closely associated with the finer hemihydrate particles than the larger dihydrate particles is the basis of procedures designed to lower the radioactivity of phosphogypsum (Palmer and Gaynor, 1984; Moisset, 1990).

It has been known for a long time that Ra and Ba co-precipitate together as sulfates (Doerner and Hoskins, 1924). The solubility product constants (25°C) for radium sulfate and barium sulfate are $10^{-10.4}$ and 10^{-10}, respectively (Sillen and Martell, 1964; Gilkeson et al., 1983). The ionic radius of Ra^{2+} is 0.152 nm, while that for Ba^{2+} is 0.143 nm (Ames and Rai, 1978). In phosphogypsum, high Ca and low pH probably result in the solubility of solid solutions dominating the pore water chemistry of Ra because adsorption is negligible under these conditions (Langmuir and Melchoir, 1985). There is evidence that nucleation of Ra sulfate may be inhibited if Ba is not present (Gilkeson et al., 1983 cited by Upchurch et al., 1991). Moisset (1980, 1988, 1990) reported that Ca, Sr, and Ba co-precipitate into small spheres which exist individually or attached to the surface of calcium sulfate crystals. Langmuir and Melchoir (1985) found brines undersaturated by 5–6 orders of

magnitude with respect to pure $RaSO_4$. The Ra-226 concentration in the brine was probably controlled by the solubility of Ra in trace solid solutions with Sr and Ba. Sebesta et al. (1981) determined the predominant particulate form of Ra and Ba in uranium waste waters to be $Ba(Ra)SO_4$.

Not all Ra-226 in phosphogypsum originates from precipitation of sulfate compounds during the wet phosphoric process. Some Ra-226 in phosphogypsum may also originate from phosphate rock particles which have survived the sulfuric acid attack.

Even though Ra is considered to be relatively immobile there are some instances where high levels have been found in groundwater systems (SENES, 1987). Radium may form a soluble sulfate species such as the neutral $RaSO_4^o$ ion pair

Table 6
U.S. Drinking Water Regulations and Canadian, European Economic Community (EEC) and World Health Organization (WHO) Guidelines[a]

Substance	U.S. maximum contaminant level[b] (mg l^{-1})	Canadian maximum acceptance limit[c] (mg l^{-1})	EEC maximum admissable concentration[c] (mg l^{-1})	WHO Guideline Value[c] (mg l^{-1})
Inorganics				
As	0.05	0.05	0.05	0.05
Ba	1.0	1.0	0.1	NS
Cd	0.01	0.005	0.005	0.005
Cr	0.05	0.05	0.05	0.05
Fluoride	4.0	1.5	NS	1.5
Pb	0.05	0.05	0.05	0.05
Hg	0.002	0.001	0.001	0.001
Nitrate-N	10.0	10.0	50	10
Se	0.01	0.01	0.01	0.01
Ag	0.05	0.05	0.01	NS
Radionuclides				
Beta particle and photon activity	4 mrem	NS[e]	NS	1 Bq l^{-1}
Gross alpha activity	15 pCi l^{-1} (0.56 Bq l^{-1})	NS	NS	0.1 Bq l^{-1}
Ra-226 + Ra-228	5 pCi l^{-1} (0.19 Bq l^{-1})	1 Bq l^{-1} (Ra-226 only)	NS	NS
Other				
Chloride	250	250	25[d]	250
Cu	1	1.0	variable[d]	1.0
Fe	0.3	0.3	300	0.3
Mn	0.05	0.05	50	0.1
Sulfate	250	500	25[d]	400
Zn	5	5	variable[d]	5.0
pH	6.5–8.5	6.5–8.5	6.5–8.5[d]	6.5–8.5
TDS[f]	500	500	NS	1000

[a]This table is only a partial list of drinking water regulations and guidelines adapted from van der Leedon et al. (1990).
[b]U.S. Inorganic and Radionuclide Categories are enforceable; Others are non-enforceable.
[c]Non-enforceable.
[d]Guide level since no maximum admissible concentration.
[e]No standard.
[f]TDS = total dissolved solids.

(Upchurch et al., 1991). However, of the alkaline earth metals Ra shows the least tendency to form complexes (Ames and Rai, 1978). Until water becomes saturated with $RaSO_4$ and precipitation occurs, $RaSO_4^o$ complexes may be a major means of transport in groundwater systems (Upchurch et al., 1991).

Radium exists only as a divalent cation and is not directly affected by redox reactions; however, bacterially mediated redox reactions can indirectly solubilize heavy metals and radionuclides such as Ra-226 from (Ba, Ra) sulfate sludges. Thus anaerobic conditions may greatly increase the mobility of Ra-226 in the environment. Fedorak et al. (1986) studied the effect of sulfate reducing bacteria on release of Ra-226 from (Ba, Ra) SO_4 uranium mine sludges. They found approximately 400 Bq l^{-1} of dissolved Ra-226 in anaerobic uranium mine waste during laboratory batch incubations when high levels of lactate were added to the samples. The fact that Ra-226 release was increased by three orders of magnitude after carbon supplementation was considered to be of great practical significance (Huck and John, 1989). The U.S. drinking water standard for Ra-226 plus Ra-228 is 0.19 Bq l^{-1}. The Canadian drinking water guideline for Ra-226 is 1 Bq l^{-1} (Table 6).

The geochemical nature of groundwater influences Ra-226 concentrations. The leachability and retention of Ra-226 in groundwater may be enhanced by a solution of high ionic strength, such as groundwater with high total dissolved solids (Kaufman and Bliss, 1977; Burnett et al., 1988). Under these conditions high concentrations of other ions may out-compete Ra-226 for adsorption sites, thereby allowing more Ra to remain in solution.

Radon. There are 27 known isotopes of Rn gas, but only Rn-222 is produced in significant amounts by phosphogypsum made from sedimentary phosphorites. Radon-222 forms from the alpha decay of Ra-226. The radioactive gas has a relatively short half-life, 3.82 days, and forms Po-218 by alpha decay. Radon-222 is an inert, noble gas which is an environmental concern because it can be highly mobile and eventually decays to form two relatively long-lived radioactive daughters, Pb-210 and Po-210. The gas is soluble in water (partition coefficient = 0.35; Conc. in water/conc. in air at 10°C), and solubility increases with decreases in temperature. Solubility in organic liquids may be several orders of magnitude greater than in water (Cothern, 1987).

Not all the Rn-222 atoms formed from Ra-226 decay are released from mineral structures. Emanation is the process whereby Rn is released from the crystal structure. The emanation coefficient is the number of Rn-222 atoms which escape from the solid phase divided by the total number of Rn-222 atoms which form from the decay of Ra-226. Emanation coefficients for Rn-222 in crystals of apatite, monazite and uraninite have been measured to range between 0.5% and 25% (Rama and Moore, 1984). Phosphogypsum typically has an emanation coefficient of approximately 15% (Roessler et al., 1979b; Pensko et al., 1980; Ackers et al., 1985). Once Rn-222 has been released from the crystal structure it is free to diffuse through the pore spaces of the Ra-226 bearing material and reach the atmosphere. The exhalation rate is the flux density of Rn-222 gas entering the atmosphere from the surface of a Ra-226 bearing material (Bq m^{-2} s^{-1}) (SENES, 1987). The factors which determine the exhalation rate of Rn-222 from a source such as phosphogypsum are the Ra-226 content and its distribution, the emanation coefficient, atmospheric pressure, and the diffusion coefficient for radon. The diffusion coefficient will vary greatly depending on temperature and moisture levels (Windham and Horton, 1980). Cracks and crusts on the surface of phosphogypsum will greatly influence exhalation rates.

As Ra-226 forms Rn-222 a high speed alpha particle is ejected from the nucleus, carrying most of the excess energy produced during the radioactive decay. The newly formed Rn-222 atom recoils in the opposite direction with a kinetic energy which is 104–105 times greater than typical bond energies (Michel, 1987). As a result, the recoiled Rn-222 atom can move within mineral structure up to a distance of 70 nm (Tanner, 1964, 1980). If the mineral surface is present within this distance the Rn-222 atom may escape the crystal and be free to enter pore air or pore water. Thus, the amount of Rn-222 which is potentially available for release from a mineral is in part related to the

surface area to mass ratio (Michel, 1987; Burnett et al., 1988). The energy of recoiling atoms is sufficiently high that some atoms cross intraparticle pore spaces and become embedded in adjacent crystal structures. Water in intraparticle pores reduces the energy of the ejected atoms, decreasing the proportion which are re-embedded in other mineral structures. Thus, water may increase the emanation coefficient. High moisture contents may decrease Rn-222 transport to the atmosphere because the gas has a relatively short half-life, and because diffusion of Rn-222 in water is several orders less than in air. Transport of Rn-222 in solution may be substantial if water is rapidly flowing through the mineral matrix in which Rn is emanating. Some Rn-222 progeny are relatively long-lived and may be transported long distances in water (Upchurch et al., 1991).

Thorium. Thorium radionuclides occur in the +4 oxidation state and form sparingly soluble compounds with hydroxides, fluoride and phosphate. Compounds of chloride, nitrate and sulfate are relatively soluble. Complexes with fluoride, chloride, nitrate, phosphate and sulfate dominate its solution chemistry. Total Th in solution decreases as pH is increased to 5. At >pH 5 further pH changes have little effect on Th concentration in solution due to the formation of $Th(OH)_4^0$. Thorium readily hydrolyzes in acidic environments. Adsorption of Th to surfaces increases with pH and decreases in soil particle size. The element has been reported to migrate mainly in polymeric colloidal form (Ames and Rai, 1978). Th-228 and Thorium-230 are more commonly found in groundwaters than is Th-232. Thorium isotopes from the U-235 decay series are not very prevalent due to the scarcity of the U-235 parent (Osmond et al., 1985).

Lead. Most Pb-210 will be partitioned into the phosphoric acid during the wet phosphoric acid process. The activity of Pb-210 in phosphogypsum will therefore be determined by the ingrowth of Rn-222 and its 3.82 day half-life. In the U-238 decay series Pb-210 is the first decay product after Rn-222 which has a half-life of any significant length (21 years). Lead-210 decays via beta-decay and is not as much of a health risk as the alpha producing radionuclides, but its long half-life assures that it will exist for long periods of time. Also significant is the fact that it decays to eventually form Po-210, which is a relatively long-lived alpha emitter (138 days). The rate of ingrowth of subsequent decay products is determined by the half-life of Pb-210. Lead speciation and solubility are controlled by Eh and pH. The element exists in the +2 and +4 oxidation states but the +2 state usually dominates. Solubility is low (2 mg l^{-1}) except in acidic environments (Upchurch et al., 1991). Lead carbonate and $PbSO_4$ are quite insoluble and often control the solubility of lead in oxidizing environments. Under reduced conditions Pb is likely to precipitate as PbS. Adsorption onto clays and organic materials may keep solution concentrations low.

Polonium. Most Po-210 is partitioned into the phosphogypsum during wet phosphoric acid production. Polonium-210 has been found to be abundant in groundwater aquifers below mined lands in Florida where it constitutes most of the gross alpha activity. This radionuclide exists in several valence states with the +4 being the most common. However, the chemistry of Po is not clearly understood (Upchurch et al., 1991). Polonium mobility is controlled by the solubility of the radiocolloids formed by complexing of the element with hydroxyl. Polonium is most mobile in acidic systems. Under alkaline systems it forms a polonium-hydroxyl radiocolloid, often co-precipitated with iron-hydroxyl colloids, which are not very mobile (Upchurch et al., 1991). Complexes between Po and organic compounds may also be important in Po mobilization (Oural et al., 1989). Upchurch et al. (1991) state that there is little direct evidence that ion exchange or redox reactions play a large role in Po mobilization. However, they do note that Po solubility may be influenced by redox reactions of S. Polonium solubility is high in reducing, sulfide rich waters. Particulate Po increases as sulfide is oxidized (Harada et al., 1989). If redox conditions and soluble organic matter levels are suitable for sulfate reduction it is likely that Po-210 will become mobile if pH is not too high.

3.4. Studies of solubility-controlling solids

There have not been very many studies which

have examined the factors which control the mobilization of trace elements and radionuclides in phosphogypsum. Most chemical studies have focused on the elemental composition of the material, or have been empirical leaching studies. Mattigod et al. (1990) and Eary et al. (1990) proposed that these types of studies should be complemented with studies which examine the thermodynamics of specific dissolution/precipitation, adsorption/desorption, and speciation reactions which occur during the weathering of industrial by-products. This latter approach permits predictions of leachate behavior under a wide range of conditions which are not possible with empirical leaching studies. If solubility-controlling solids of an element are present in a waste, or may precipitate from it, then the long-term aqueous concentrations can be predicted from thermodynamic data and adsorption/desorption reactions may be ignored (Eary et al., 1990). Even though thermodynamic data are available for pure-phase secondary solids containing trace elements, there is a lack of data for solid solutions, especially those for radionuclides. If conditions for solubility-controlling solids are not present, or if kinetics are too slow, then dissolution rates and/or adsorption reactions will dominate (Eary et al., 1990). In nature non-equilibria may occur as a result of slow kinetics or microbial catalysis. Changes in the oxidation state of some elements will also influence the above processes. Acidic, aerobic conditions would be expected to define the pore water chemistry of phosphogypsum, however reduced conditions may develop near the base of a stack. The pH of phosphogypsum may approach neutrality as the material ages.

The application of chemical speciation to predict the mobility of trace elements in phosphogypsum and phosphogypsum process water is lacking. Of the little speciation data which has been published, most has been for the major rather than for the minor elements. Murray and Lewis (1985) used GEOCHEM to predict the fate of fluoride, orthophosphate and sulfate from phosphogypsum leachate as it reacted with simulated soil systems. Their results will be elaborated in a later section. Lewis (1988) extended this work further by examining the fate of Ra-226 species originating from uranium mill waste solutions in simulated soil systems using GEOCHEM. The simulated and experimental results did not match very closely. The inconsistency was explained by Lewis (1988) as being the result of a poor data base for Ra-226 species, particularly for mixed-solid species. Radium is known to form solid solutions with some elements such as Ba and Sr (Langmuir and Melchoir, 1985); however, thermodynamic data for Ra solid solutions are not complete.

May and Sweeney (1984b) evaporated the leachate water from phosphogypsum but X-ray diffraction of the evaporite did not help to identify any trace element compounds. Literature studies of phase equilibria in saturated gypsum solutions were used to identify possible trace element compounds. The expected specific compounds of trace elements were sulfates, except for the Ca compounds of arsenate, chromate and selenate.

Luther and Dudas (1993) examined solution extracts from 80-day batch incubation studies of phosphogypsum, phosphogypsum-soil mixtures and soil alone. Speciation of major and trace elements was performed using GEOCHEM. As pH was raised due to soil addition most free cations decreased, OH^- interactions increased and PO_4^{3-} and SO_4^{2-} interactions decreased. Concentrations of Cd, Fe, Ni, P, Sr, V, and Zn in solution decreased by close to an order of magnitude. Soil addition increased Ca^{2+} and Cd^{2+} interactions with SO_4^{2-}. AsO_4^{3-}, CO_3^{2-}, PO_4^{3-} and SeO_3^{2-} were mainly combined with H^+ in phosphogypsum leachate and the proportion decreased with neutralization. Nitrate, SO_4^{2-} and SeO_4^{2-} existed mainly in the free state and this fraction increased with neutralization.

Luther and Dudas (1993) also compared ion activities predicted by GEOCHEM with theoretical levels using solubility constants for potential solubility-controlling solids of Al, As, Ca, Cd, Cu, Fe, P, S, Se, Si and Zn. Aluminum activities were consistent with the presence of the solubility-controlling solids of alunite, basaluminite, gibbsite and jurbanite. Under acidic conditions and high sulfate levels the aluminosulfate minerals alunite and basalunite were predicted to be the most stable (O'Brien and Sumner, 1988; Alva et al., 1991).

Solubility-controlling solids for the trace ele-

ments could not be identified by Luther and Dudas (1993) because solutions were undersaturated relative to the potential minerals for which thermodynamic data were available. Thus the effects of precipitation/dissolution and adsorption/desorption could not be resolved. Spiking the material with trace elements might allow for the prediction of solubility-controlling solids if they existed (Rai and Szelmeczka, 1990). The batch incubations showed that Cd concentrations were high in phosphogypsum pore water but concentrations of this element, along with Cu and Zn, decreased greatly with increases in pH. Arsenic and Se concentrations did not decrease greatly with pH increases and, along with SO_4^{2-} and F^-, were identified as potentially posing an environmental risk if leached downwards into groundwater systems.

4. Environmental concerns related to the storage of phosphogypsum

Most of the phosphogypsum produced is stored in stacks (Carmichael, 1988). A recent final ruling by the U.S. E.P.A. requires that all phosphogypsum be placed in stacks or mines (Federal Register, 1990). Environmental contamination resulting from phosphogypsum storage may occur from: (i) atmospheric contamination with fluoride or other toxic elements; (ii) groundwater pollution with mobile anions, acidity, trace elements or radionuclides; (iii) radon gas; (iv) inhalation of radioactive dust; and (v) direct exposure of gamma radiation. Other concerns with storage include surface runoff (Rydzynski, 1990), and erosion and stability of the stacks. Several authors have published methods of reducing fluoride, radionuclides and heavy metals in phosphogypsum by treatments before, during or after the wet phosphoric acid process (Becker, 1989; Jdid et al., 1986; Kazak et al., 1988; van der Sluis et al., 1988; Habashi, 1989; Moisset, 1990). Mitigation and closure of phosphogypsum storage sites are discussed by Berish (1990) and Norlander (1988).

4.1. Atmospheric fluoride

Fluoride gas emission is only a concern with operational stacks; however, transport of fine dust particles containing F^- is a potential problem for both operational and inactive stacks. Phosphate rock may contain 4% fluorine which forms HF during the acidulation process. Fluoride remains in the liquid phase but during processing gaseous SiF_4 and gaseous HF may be formed under high temperature conditions. When phosphogypsum is sluiced to the stack some gaseous F^- may be evolved; however, most plants use scrubbers to remove F^-.

Linero and Baker (1978) evaluated previous F^- emission rate studies to determine a F^- emission factor which could be used for predictive modelling. None of these studies were ideal, however it was concluded that the characteristic emission factor for cooling ponds fell in the range of 0.1–10 lb acre^{-1} day^{-1} (30–3400 μg cm^{-1} 30 days^{-1}). Modelling predicted that ambient F^- concentrations near a typical pond would be sufficiently high to require technologies to control F^- emission.

SENES (1987) discussed the F^- monitoring programs in place at two sites in Canada. The Ontario site was the focus of two phytoxicological surveys. The results of this monitoring showed that probably only operating facilities result in elevated ambient F^- levels. The Ontario Ministry of the Environment (OME) established 35 μg g^{-1} as the upper limit of normal background concentration of F^- in foliage. During plant operation foliage samples exceeded this level as far away as 6 km from the plant site (McLaughlin, 1986). Wild grape, a plant very sensitive to F^-, showed damage in the areas surrounding the plant site.

Fluoridation rates in the area surrounding the Ontario site were measured by the OME. Annual averages ranged from 18 μg F^- 100 cm^{-2} 30 days^{-1} at a station 5.4 km away to as high as 927 μg F^- 100 cm^{-2} 30 days^{-1} at a station close to the operating site. Seasonal variation of ambient fluoridation levels was observed to be greatest in the summer. Fluoridation rates declined greatly when operation of the phosphoric acid plant ceased (SENES, 1987).

Ambient fluoridation levels were also measured immediately adjacent to the ponds and plant at an operating site in Calgary, Alberta. Seasonal and spatial variation was observed with rates ranging

from a low of 6 μg F 100 cm^{-2} 30 $days^{-1}$ to a high of 5170 μg F 100 cm^{-2} 30 $days^{-1}$. Maximum air quality guidelines for fluoridation levels are 40 μg 100 cm^{-2} 30 $days^{-1}$ in Alberta, and 80 and 40 μg F 100 cm^{-2} 30 $days^{-1}$ in Ontario for growing and non-growing seasons, respectively.

4.2. Groundwater pollution

Groundwater contamination may occur from process water seepage during operation of a stack or through the long-term downward leaching which occurs when rainwater infiltrates through an inactive stack.

Several studies have investigated groundwater pollution or the potential leachability of phosphogypsum constituents. The results are not consistent although it is clear that the potential for groundwater pollution under a phosphogypsum stack is a concern in some situations.

Acidic seepage waters may be buffered by alkaline subsoils and groundwaters, thereby reducing the mobility of certain heavy metals (e.g. Ni, Co,

Table 7
Reported values for chemical composition of phosphogypsum process water (units are mg l^{-1} unless otherwise stated)

Parameter	Source				
	Becker (1989)	Miller and Sutcliffe Jr. (1982)		Murray and Lewis (1985)	Rouis and Bensalah (1990)
		AMAX[a]	USSAC[b]		
Al	160 (64–210)[c]		400	100–500	0.41
As		0.92	0.63		
B		3.0	2.7		
Ba		0.50	0.50		
Ca	1430 (350–3360)[c]	30	30	350–1200	1654
Cd		0.51			0.62
Cl		15		200	1520
Co		0.17	0.5		0.18
Cr		0.68	3		2.7
Cu		0.21	0.5		0.08
F	10 000 (900–12 000)	4300	7700	3000–10 000	5539
Fe	105 (77–770)[c]	63	41	70–300	12.8
Hg		0.2 μg l^{-1}	0.2 μg l^{-1}		0.6
K	208 (10–370)[c]	220	110		62
Mg	240 (36–350)[c]	120	52	240	182
Mn		6.1	130	8	
N[f]		1780	142		
Na	1480 (280–2000)[c]	2200	790	1600	2556
Ni		1.5	0.42		
P_2O_5		9850[e]	21 000[e]	6000–12 000	4015
Pb		0.08	0.11		0.18
SiO_2		2800	3000	2000–4000	2018
SO_4	4800 (2800–10800)[d]	4700	5000		5385
Sr		0.41	0.92		28
Ti					0.42
Zn		2.7	3.7	1.0–1.8	4.0
pH	1.5 (1.2–2.5)	1.8	1.3		1.8

[a]Cooling water (Sample S2) at AMAX Phosphate Inc., central Florida.
[b]Cooling water from return ditch (Sample S2) at USS Agri-Chemicals plant, central Florida.
[c]Converted from oxide values.
[d]Converted to SO_4 from reported SO_3.
[e]Converted to oxide from total P.
[f]Organic N plus ammonium N.

Cu) (SENES, 1987). However, other chemical species such as SO_4^{2-} and F^- are not affected as much by pH changes from the stack to the subsoil. Site specific conditions which may mitigate the impact of possible contaminants on groundwater are: (i) suitable subsurface geology which can neutralize acidic seepage; (ii) construction of the stack on an impervious layer; and (iii) construction of interceptor wells or ditches. Other sources have reported methods of reducing seepage of contaminants from active and inactive stacks (Gipson, 1985; Wissa, and Fuleihan, 1980; Wrench and Smith, 1986; Kleinschmidt, 1990; Rouis and Bensalah, 1990).

Process water. The recycled process water used to sluice phosphogypsum out to the stacks is aci-

Table 8
Reported radionuclide activities (Bq l^{-1}) in phosphogypsum process water

Isotope	Activity[a]	Site description	Reference
Ra-226	1.9	AMAX[b]	Miller and Sutcliffe Jr., 1982
	3.2	USSAC[c]	
	2.6	Plant A	Guimond and Windham, 1975
	3.2	Plant B	
	2.0	Plant C	
U-234	70	AMAX	Miller and Sutcliffe Jr., 1982
	140	USSAC	
	28	Plant A	Guimond and Windham, 1975
	65	Plant B	
	25	Plant C	
U-235	2.5	AMAX	Miller and Sutcliffe Jr., 1982
	8.1	USSAC	
	1.3	Plant A	Guimond and Windham, 1975
	3.7	Plant B	
	1.3	Plant C	
U-238	72	AMAX	Miller and Sutcliffe Jr., 1982
	120	USSAC	
	27	Plant A	Guimond and Windham, 1975
	68	Plant B	
	25	Plant C	
Th-227	0.3	AMAX	Miller and Sutcliffe Jr., 1982
	2.3	USSAC	
Th-228	0.67	AMAX	
	0.63	USSAC	
	0.11	Plant A	Guimond and Windham, 1975
	0.15	Plant B	
	0.03	Plant C	
Th-230	4.2	AMAX	Miller and Sutcliffe Jr., 1982
	69	USSAC	
	3.2	Plant A	Guimond and Windham, 1975
	15	Plant B	
	0.3	Plant C	
Th-232	0.52	AMAX	Miller and Sutcliffe Jr., 1982
	0.89	USSAC	
	0.14	Plant A	Guimond and Windham, 1975
	0.23	Plant B	
	0.15	Plant C	

[a]Dissolved plus suspended activities.
[b]Cooling water, Sample S2 at AMAX Phosphate Inc.
[c]Cooling water from return ditch, (Sample S2) at USS Agri-Chemicals Plant.

dic. Sulfuric, phosphoric and fluoridic acids reside in the phosphogypsum pores after acidulation and filtration. Consequently, elements solubilized from phosphate rock during the acidulation process may remain in solution. This process water is present in cooling ponds and also within the porosity of the phosphogypsum stack.

The species solubilized during acidulation include As, Cd, Cr, Pb, Na, F^-, Mn, Fe, SO_4^{2-}, U and Th (Roessler, 1979a; Berish, 1990). In addition to toxic elements, the process water contains high levels of total dissolved solids (Rea and Woods, 1985). Elemental composition of process waters is reported in Tables 7 and 8. The waters do not meet many of the limits set for drinking water regulations and guidelines (Table 6).

Laboratory studies. Murray and Lewis (1985) determined the extent to which natural geological materials could remove fluoride, sulfate and orthophosphate from phosphogypsum leachate under laboratory conditions using graded, serial batch leaching systems. The minerals investigated were sand, Ca-montmorillonite, kaolinite, calcium carbonate and iron (III) hydroxide. The chemical equilibrium model GEOCHEM was used to speciate the leachate solutions. Calcium carbonate removed large proportions of F^- and orthophosphate and smaller proportions of sulfate by precipitation as CaF_2, calcium phosphate and/or calcium fluorophosphate and $CaSO_4$. Sufficient calcium carbonate was needed to maintain a high solution pH, otherwise redissolution of F and orthophosphate occurred. Sand only removed small quantities of F^-, probably by anion adsorption. Both kaolinite and montmorillonite removed large quantities of soluble F and orthophosphate from solution. The removal increased with increasing pH, likely due to a combination of complex formation, the degree of phosphate ionization and changes in clay charge characteristics. The removal of F^- by kaolinite was probably due to positive charge development on the clay. At pH 4, 84% of F existed as free F^- and the AlF_4^- complex. Iron(III) hydroxide had little effect on F^- or orthophosphate removal when mixed with clays but markedly increased SO_4^{2-} removal when Ca was abundant, probably by the formation of Ca phosphate complexes which reduce competition with sulfate for adsorption on clays or Fe (III) hydroxide. According to Murray and Lewis (1985) calcareous strata below phosphogypsum may be very effective in precipitating F^- and orthophosphate.

May and Sweeney (1984b) evaluated the leachability of Ra and elements the E.P.A. has classified as toxic by using the standard E.P.A. 'EP' extraction procedure (Federal Register, 1980). Additional elements (Cu, Ni, K and Na) were included in the analysis. The concentrations of toxic elements in the extract were all below E.P.A. maximal concentrations, therefore the material was considered non-toxic by E.P.A. standards. The authors estimated that the inclusion of Ra into the phosphogypsum crystal structure would be 89% of the amount originally present, indicating that very little Ra would be leached. May and Sweeney (1984b) estimated the Ra to move at approximately 1/200 the seepage rate.

SENES (1987) conducted leachate studies on two composite phosphogypsum samples taken from sites located at Dunnville, Ontario and Calgary, Alberta. The Ontario material was from an inactive stack while the Alberta material was taken from an active stack. The leachate test involved agitating the solid in distilled water (1:10 ratio) for 24 h followed by filtering. All measured concentrations of toxic elements were below the E.P.A. criteria, although the Cd and Cr concentrations from the Alberta site were much greater than values found at the Ontario site or by May and Sweeney (1984a) in Florida phosphogypsum. The Alberta phosphogypsum was acidic due to the presence of residual process water. Relatively high concentrations of Al, Cd, Cr, Fe, Mg, Ni and V were attributed to the low pH and relatively high solubility of the metallic hydroxides (SENES, 1987). The leachate from the Ontario phosphogypsum had a pH of 6.02. Although it contained elevated levels of Ca, SO_4^{2-}, P, F^-, and Al, they were lower than those from the Alberta material. Heavy metal concentrations were much lower than in the Alberta phosphogypsum leachate. According to SENES (1987), the results showed that leachate from fresh phosphogypsum exceeded both mining discharge objectives and Canadian drinking water standards. Aged phosphogypsum

may meet mining discharge objectives except for P, Al and possibly Cd. Fluoride and SO_4^{2-} levels are likely to be exceeded even in aged phosphogypsum material (SENES, 1987). Lead-210, a relatively long-lived radioactive product from the U-238 decay chain, was 100-fold greater in the Alberta phosphogypsum leachate than in the Ontario phosphogypsum leachate and exceeded the World Health Organization Guideline for beta particle activity (1.0 Bq l^{-1}) by three times.

Naff (1984) conducted a leachate study to determine the potential environmental impact of phosphogypsum from Mobil Chemical Corporation. Fresh, aged and stabilized phosphogypsums were analyzed using the standard E.P.A. EP extraction procedure. The results were within the permissible E.P.A. limits for toxicity, however SO_4^{2-} and fluoride levels exceeded drinking water standards.

Luther et al. (1993) determined the equilibrium concentrations of major and trace elements in phosphogypsum pore water taken from an inactive phosphate plant in southern Alberta in order to evaluate the groundwater contamination potential of phosphogypsum. Some extracts had higher levels of As and Cr than those found by May and Sweeney (1984b), but all pore water samples were more concentrated in Cd and Se. Luther et al. (1993) determined that all extract samples exceeded Canadian drinking water guidelines (CDWG) for Cd, Se, SO_4^{2-} and total dissolved solids. Some samples exceeded CDWG for As, Cd, Cr, Cu, Fe, Mn, Na, NO_3-N and Zn (Table 6). The pH of the pore water extract was 3.4, which is below CDWG. Fluoride levels were not measured by Luther et al. (1993); however, Roberts-Thorne (1990) determined levels to be 26 $\mu g\ g^{-1}$ at the same site a few years earlier. Canadian DWG requires fluoride to be $<1.5\ \mu g\ g^{-1}$ (Health and Welfare Canada, 1993).

Field studies. SENES (1987) summarized work by Miller and Sutcliffe (1982) for two operational stacks in central Florida (AMAX Phosphate Inc. and USS Agric-Chemicals Ltd.) which are located on limestone bedrock that is overlain by phosphatic clay deposits and a surficial sand layer. Groundwater in the area is characterized by hard, calcium magnesium bicarbonate water with low SO_4^{2-} and Cl^- concentrations. Both stacks caused slight distortions in the groundwater level which reflected recharge of water from the stack and pond areas. Significant degradation in groundwater quality was detected at the two sites. Many chemical parameters showed levels up to several orders of magnitude greater than natural groundwater concentrations. Relative to background concentrations, the groundwater below the two sites showed elevated concentrations of Si, Na, SO_4^{2-}, F^-, hardness, P and N. Concentrations of Cu, Mo and Zn were also elevated. Low pH was also found near the gypsum stacks and cooling ponds at the USS site. Movement of contaminants in a plume was observed at both Florida sites. Groundwater 600 m from the USS stack showed sulfate concentrations which were 450 times greater than background levels. Groundwater 460 m from the AMAX stack had sulfate concentrations up to 1900 mg l^{-1} (SENES, 1987). Selected members from the U-238, U-235 and Th-232 decay chains were also measured in the groundwater below the AMAX site. Radium-226 was measured below the USS site. All radionuclides, except for Ra-226 at the USS site, were within drinking water standards, however U-238 was elevated over background in some samples. At both sites elevated levels of Ra-226 were observed hundreds of meters from the stacks, indicating Ra-226 migration through the groundwater systems (SENES, 1987).

SENES (1987) reviewed groundwater studies which have been conducted near phosphogypsum stacks in Alberta at sites operated by three fertilizer manufacturers. All sites are located on relatively flat terrain underlain by glacial till. Near surface groundwater quality is poor so drinking water and irrigation water is obtained from deep groundwater or surface water. It was not possible to compare groundwater quality between sites because different monitoring criteria were used at each site. The criteria set for background levels were conservative and were based on taking the lowest values observed in observation wells to represent background levels. Sulfate concentrations were found to be much greater than apparent background. Fluoride concentrations of up to 32 mg l^{-1} were detected, which are several orders of magnitude greater than background. SENES

(1987) did not think that heavy metals would be very mobile in these groundwater systems because pH values ranged between 6.5 and 8.7. Levels of Ca, P and N species were elevated above background in some wells.

May and Sweeney (1984b) supplemented their laboratory studies (see above) of the leaching characteristics of phosphogypsum stockpiles by detailed sampling through a short section both above and below the ground:phosphogypsum interface. Subsurface analysis was not available prior to phosphogypsum stacking and was estimated using averages from similar geological materials. It was concluded that Ra-226 and metallic elements were not leached from the phosphogypsum stockpiles.

Toxicity analysis of phosphogypsum was conducted by May and Sweeney (1982, 1984a, 1984b) on nine Florida stacks in order to assess the potential environmental impact of the material. Both active and inactive stacks were included in the study. Part of the study involved measuring the total elemental composition throughout the stack profile. The researchers hypothesized that if significant leaching of elements occurred, there would be a non-uniform distribution of elements down though the stack. They concluded that significant leaching had not occurred because a uniform distribution of elements was found.

Berish (1990) summarized a groundwater study conducted in Florida by Bromwell and Carrier (1987). Data from surficial groundwater at four phosphogypsum sites in Florida were used to calculate distances downstream from a theoretical phosphogypsum site at which contaminant concentrations would not exceed E.P.A. Drinking Water Standards. Concentrations of Se, Ag and F^- were attenuated quickly and were below the E.P.A. maximum contaminant levels for Primary Drinking Water Standards within 100 feet of the source. Lead and As concentrations met these standards within 300 feet and 800 feet, respectively. Cadmium and Cr were more mobile and were not attenuated until up to 1200 feet from the source. Iron, SO_4^{2-}, Mn and total dissolved solids were very mobile but limited data made it difficult to make an accurate estimation of the size of the impact zone. However, it was estimated that the non-exceedance zone would be greater than 610 m from the source and would be highly dependent on site specific geologic and hydrologic conditions. Shallow surficial aquifers were the main groundwater systems contaminated by phosphogypsum stacks.

Rouis and Bensalah (1990) investigated the groundwater contamination below a phosphogypsum stack in Tunisia. The pH of the groundwater near the stack was less than 2. It was neutral 200 meters downstream from the stack. Phosphate and F^- levels near the stack were as high as 16300 and 8800 mg l^{-1}, respectively. Mercury and Mo levels were as high as 0.60 and 0.19 mg l^{-1}, respectively. The region of high groundwater contamination extended 100 to 400 meters downstream from the phosphogypsum stack.

Other studies have investigated the groundwater pollution potential of phosphogypsum which has been used as a base for road construction (Chang et al., 1989; Bandyopadhyay et al., 1990; Nifong, 1990). These studies reported no adverse effects of phosphogypsum on groundwater quality.

4.3. Radon gas and other radioactive exposure

Roessler (1986) summarized the pathways of radioactive exposure originating from phosphogypsum to humans. Exposure to Rn-222 gas is one of the greatest health concerns. This section will review the studies which have investigated the magnitude of Rn-222 gas evolution and the significance of these rates. Other forms of aerial exposure, such as radioactive dust particles and direct gamma radiation from phosphogypsum stacks, will also be included in this section. Before discussing Rn-222 it is appropriate to summarize simple dosimetry, the means by which radioactive exposure is measured. A more comprehensive description of the subject is offered by references such as Cothern (1987) or Lao (1990).

Several terms are used to describe the health effects of radionuclides such as Rn-222 and its progeny. The working level (WL) has been in use since 1955 and describes the potential alpha energy concentration of radon progeny. A WL is defined as the exposure rate of 1.3×10^5 MeV (2.08×10^{-5} J) of potential alpha energy/liter of air. This is the energy released from the total decay of short-

lived Rn-222 progeny to Po-214 in radioactive equilibrium with 3700 Bq m^{-3} (100 pCi l^{-1}) of Rn-222. The working level month (WLM) corresponds to an exposure of 1 WL during 1 month (approx. 170 h). In terms of radon progeny concentration, a WL of 0.001 is representative of average outdoor concentrations. Average indoor levels are 0.004 WL. The level recommended for remedial action by the U.S. National Council on Radiation Protection and Measurements (NCRP, 1984) is 0.04 WL. Assuming 0.5% equilibrium between radon and its progeny, this is equivalent to a radon concentration of 300 Bq m^{-3} (8 pCi l^{-1}). This results in a continuous exposure rate of about 2 WLM/year (Mills and Egan Jr., 1987). In Canada, remedial measures are recommended when average indoor Rn-222 daughter concentrations exceed 0.02 WL (NCRP, 1984).

Walsh (1990) provided a theoretical argument that current mining risk coefficients, such as the WL, significantly overestimate environmental radon risk because miners are exposed to a complex atmosphere that contains many substances which may potentially cause cancer. Current lung cancer risk assessments assume that radon progeny alone are responsible for differences between miners and control populations.

The absorbed dose, D, refers to the average density of energy absorbed by a mass of cells. In the SI system the unit is the Gray (Gy), equivalent to J kg^{-1}. The conventional unit for absorbed dose is the radiation absorbed dose (rad), which is equivalent to one hundredth of a Gray.

The dose equivalent, H, is a measure of both the energy absorbed by a mass and the biological impact of the absorbed energy. Measured in Sieverts (Sv), it is the product of the absorbed dose, D, the quality factor, Q, and a factor, N (usually 1), which incorporates other modifying factors. The conventional unit for H is the radiation equivalent in man (rem), which is equivalent to one hundredth of a Sievert. The quality factor, Q, is small for gamma and X-rays (1), intermediate for neutrons (5), and high for alpha particles and other heavy nuclei (20). Thus for gamma radiation the radiation absorbed dose (rad) is usually the same as the radiation equivalent in man (rem). The dose equivalent of an organ is calculated by multiplying H by a weighting factor which takes the radiosensitivity of an organ into consideration. The NCRP (1984) recommendation for general public continuous exposure to gamma radiation above background is 1000 mrem (10 mSv) $year^{-1}$. Typical exposure to background gamma radiation in the U.S. is 0.28 mSv $year^{-1}$ (28 mrem $year^{-1}$). Canadian estimates are 20% lower (NCRP, 1987).

The effective dose equivalent, (H_E), is a measure of the total risk to the individual and is calculated by summing the dose equivalents of all the organs in the body. Both H and H_E are measured in Sv. The annual effective dose equivalent for all sources of natural background radiation is approximately 2 mSv $year^{-1}$, which is approximately equal to 200 mrem $year^{-1}$ (UNSCEAR, 1982; Cothern, 1987).

Field studies. A number of studies have investigated radon exhalation rates, ambient radon levels and other forms of radioactive exposure at phosphogypsum stacks. To put these values in perspective, typical exhalation rates from soil, the largest source of background radon in the environment is approximately 0.5 Bq m^{-2} s^{-1} per Bq Ra-226 g^{-1} soil (NCRP, 1987). The average concentration of Rn-222 in the global atmosphere is about 3.7 Bq m^{-3}, however concentrations may be 10-times higher over some land areas. Typical Rn-222 levels near open ground are about 5 Bq m^{-3} (Eichholz, 1987; Michel, 1987).

Windham and Horton (1980) reported the exhalation rates of Rn-222 from two active phosphogypsum stacks in Polk County, Florida over several weeks. The mean exhalation rate was 1 Bq m^{-2} s^{-1} although measured rates varied by almost two orders of magnitude. Guidry (1990) reported radon flux from a phosphogypsum stack in central Florida to range from <0.004 Bq m^{-2} s^{-1} over ditches and beaches on the stack to 3.6 Bq m^{-2} s^{-1} near a roadway on top of the stack. A wide range of variation was observed on the stack, likely due to differences in crusting.

NESHAPS (1989) summarized by Berish (1990) reported Rn-222 exhalation rates from active and inactive stacks in Florida. The greatest flux rates were from the top of dry non-crusted stacks which were active. This material averaged about 0.7 Bq m^{-2} s^{-1}. In contrast, exhalation rates were less

than 0.04 Bq m^{-2} s^{-1} from cooling ponds and ditches. Flux from the top of an inactive stack only averaged 0.15 Bq m^{-2} s^{-1} but flux from the sides of a different inactive stack was about four times greater. NESHAPS (1989) also estimated total Rn-222 fluxes from many stacks throughout Florida. Flux rates were estimated to range between 0.09 and 0.34 Bq m^{-2} s^{-1}. The computer codes AIRDOS-EPA and DARTAB were used to estimate the maximum exposed individual and also the collective risks of the regional population to Rn-222. Meteorological conditions and distance from the stacks were considered. The maximum exposed individuals were estimated to receive doses $<6 \times 10^{-5}$ WL above the natural background outdoor level. Collective risk assessment estimated that less than one fatal cancer in 20 years would occur due to the presence of phosphogypsum stacks. Based on this work, the U.S. E.P.A. recently adopted an average 0.74 Bq m^{-2} s^{-1} limit on Rn-222 emissions from phosphogypsum stacks (Federal Register, 1989).

Horton et al. (1988) reported Rn-222 concentrations around the perimeter of 5 phosphogypsum stacks 1 m above ground level. Natural background levels, determined at nine locations greater than 8 km from any phosphogypsum stack, averaged 0.0052 Bq l^{-1}. Average concentration at the base of the phosphogypsum stacks was 0.024 Bq l^{-1}. Roessler (1985) reported Rn-222 concentration to range between 0.011 and 0.015 Bq l^{-1} on or close to a phosphogypsum stack. Concentrations decreased to background within 1000 m.

SENES (1987) found Rn-222 exhalation rates from some stacks at Ontario (clay or topsoil covered stacks) and Alberta (active with bare phosphogypsum dikes with water-filled ponds) to range between 0.037 and 1.1 Bq m^{-2} s^{-1}. A typical value of 0.37 Bq m^{-2} s^{-1} was incorporated into the air dispersion model ISC-LT (Wackter, 1986) which estimated Rn-222 air concentrations under meteorological conditions representative of the two sites. At Ontario, it was predicted that maximum annual average Rn-222 concentrations 100 m from non-water covered, bare phosphogypsum stacks would be 1.1–1.9 Bq m^{-3} (0.0011–0.0019 Bq l^{-1}). Concentrations 100 m from water covered stacks would be approximately 0.19 Bq m^{-3} (0.00019 Bq l^{-1}). Some measured background levels in the vicinity were higher than this. The results for the Alberta site were similar in that predicted Rn-222 concentrations 100 m from the stacks were indistinguishable from normal background levels. SENES (1987) also measured ambient Rn-222 concentrations 1–1.5 m above stacks covered with clay in Ontario. The average concentration of 0.011 Bq l^{-1} was not statistically different than background levels (0.0074 Bq l^{-1}) for the area. Radon-222 concentration above water ponds at a phosphogypsum stack in southern Alberta averaged 0.024 Bq l^{-1}, which was not statistically different from the natural background level of 0.017 Bq l^{-1}.

Airborne particulate matter originating from phosphogypsum piles by wind erosion or operations on the stack is also a potential source of radioactivity. Wind erosion is usually not a serious problem on stacks because inactive stacks develop a crust while active stacks generally have a high moisture content which reduces blowing particles (Berish, 1990). NESHAPS (1989) found that annual radionuclide transport from a phosphogypsum stack was very low and the associated health risks were much less than those related to Rn-222 emissions. Similar findings were found by Western and SENES (1983). Air samples were taken 0.8 km south of one phosphogypsum pond in southern Alberta and analyzed for U, Th-230, Ra-226, Pb-210 and Po-210. All radionuclides except Ra-226 were within background levels. The annual Ra-226 intake was estimated to be equivalent to 2.5 μSv which is much less than 2 mSv, the typical annual exposure to natural background radioactivity.

Phosphogypsum stacks are a direct source of gamma radiation due Ra-226 and its daughter radionuclides. Horton et al. (1988) reported gamma radiation 1 m above the surface of 5 phosphogypsum stacks. Average gamma exposure was 33 μrads h^{-1} (33 μrem h^{-1}). Berish (1990) stated that only people spending long periods of time working on the stack, or living immediately adjacent to it, would be subjected to a health risk because irradiation decreases exponentially with distance. Roessler (1986) (see below) did not think this level of gamma exposure posed an environmental health risk.

Laiche and Scott (1991) conducted a study to determine the potential radiological exposure for people working at the Freeport phosphogypsum pile in Louisiana. Gross gamma exposure rates were measured 1 m above the stack surface. Air samples were also obtained from the same location. The measured gross gamma exposure rates averaged 0.368 μSv h^{-1}. The corresponding working year exposure would be 0.48–0.68 mSv above background. This level is low because it represents <10% of the annual dose limit for the general public in unrestricted areas (NCRP, 1984). Radon daughter concentrations measured on the stack ranged between 0.0006 and 0.001 WL, while airborne Ra-226 concentrations were indistinguishable from background.

Roessler (1986) conducted a detailed analysis of the radiological hazards associated with phosphogypsum produced from central Florida rock. He used radiological characteristics of phosphogypsum from a number of sources to determine the exposure hazard of the gamma radiation and air borne radioactivity in the immediate vicinity of the phosphogypsum piles. It was determined that individuals working on a phosphogypsum stack for a year (2000 h) would be subjected to a gamma radiation dose equivalent of 60 mrem. The occupational exposure limit is 5000 mrem $year^{-1}$. Measured radon concentrations were equal to or less than 0.015 Bq l^{-1} which corresponds to <0.004 WL. This level was equivalent to typical Florida indoor radon concentrations and 10-times less than the level set by the NCRP for remedial action.

Guidry (1990) conducted a detailed analysis of the radon emissions and gamma radiation irradiated from a phosphogypsum stack in central Florida. Radon emission data and measurements of airborne Ra-226 in particulate matter were utilized in the ISCLT atmospheric model to estimate the environmental impact of the stack. The receptor sites for the radiological assessment were located at the nearest point of general public access to the facility, approximately 2000 m from the stack, and also at the location of the maximum exposed individual (MEI). Estimated maximum radon daughter levels at the nearest public access point corresponded to 0.000065 WL while the maximum concentration at the location of the MEI was less than half of this amount. It was estimated that deposition of Ra-226 in particulate matter for 1000 years would increase soil Ra-226 <0.1%.

5. Utilization of phosphogypsum in agriculture

Many studies have reported the effects of applications of phosphogypsum on nutrient levels and the physical and chemical properties of agricultural soils. The benefits of phosphogypsum have been documented as amendments for: (i) highly weathered soils, with relatively low exchange capacities and/or low levels of extractable nutrients; (ii) soils with high sodicity resulting in dense subsoil horizons, and those with variable sodicity at the surface which are prone to dispersion and crusting; (iii) acid soils with high levels of Al; and (iv) calcareous soils. Crop yields and quality of a variety of fruit, vegetable, grain, forage, and oilseeds have generally been found to be higher on phosphogypsum amended soils. The wide scale use of phosphogypsum appears to be restricted until concerns regarding associated natural radionuclides, F^-, heavy metals, effect on nutrients, potential as a source of P in surface water pollution, and economic considerations are more fully addressed. Despite these environmental concerns regarding phosphogypsum, some countries have made wide-scale use of the by-product as a soil amendment (Beretka, 1990; Novikov et al., 1990). Phosphogypsum has also been used in agriculture as a feed additive for livestock (Golushko, 1984) and as a fertilizer amendment to reduce ammonia volatilization from urea fertilizer (Boyrakli, 1990), however, use as a soil amendment has been reported most extensively.

5.1. Source of plant nutrients

In plant nutrition studies, phosphogypsum has been used as a source of Ca, S, and P on a broad range of soils differing in pH and fertility. The effectiveness of phosphogypsum as a nutrient source has been attributed to its relatively rapid dissolution rate and its capacity to supply relatively large amounts of soluble nutrients during critical phases of crop growth (Malavolta et al., 1987; Bianco et

al., 1990; Gascho and Alva, 1990; Singh et al., 1990). While P_2O_5 comprises a rather small percentage of phosphogypsum material (<1%), high application rates may significantly increase available soil P (Broadbent et al., 1989; Khalil et al., 1990).

Some studies have described the influence of phosphogypsum on the availability and uptake of other nutrients. Phosphogypsum increased the availability of Fe and Mn through a localized acidifying action around roots, and increased the availability of N, P, K, and Mg in calcareous soils (Khalil et al., 1990; Singh et al., 1990). Magnesium and/or K displaced from the exchange complex by Ca derived from phosphogypsum may be subsequently leached from the zone of interest (Pavan et al., 1987; Sumner et al., 1988; Gasho and Alva, 1990). However, excess Mg and K have been linked to peanut pod rot and leaching of these cations from the pegging zone (0–8 cm) had a beneficial effect on production (Gasho and Alva, 1990).

The beneficial effect of phosphogypsum for controlling diseases is noted in some studies. Phosphogypsum either directly influenced the reduction of phytophthora infection of citrus roots or affected plant nutrition in a way which depressed fungus development on the roots (Smith et al., 1989; Nemec et al., 1990).

5.2. Reclamation of acid soils

The need to develop practical methods to ameliorate subsoil acidity is important because many acid soils in tropical and subtropical areas are used for food production. Phytotoxic Al levels, sometimes accompanied by deficient Ca levels and/or clay hardpans, may restrict root exploitation of subsoil horizons (Shainberg et al., 1989). Crops, grown on such soils, are unable to use moisture and nutrients below ameliorated surface horizons.

When phosphogypsum is applied to acid soils, field and lab studies have found: (i) decreased levels of exchangeable and solution Al; (ii) increased levels of exchangeable and solution Ca; (iii) small and/or somewhat variable effects on pH; and (iv) enhanced root growth (Pavan et al., 1987; O'Brien et al., 1988; Alva et al., 1988, 1990, 1991; Alva and Sumner, 1990; Mathews and Joost, 1990). The formation of less phytotoxic ion pairs and complex ions, mineral precipitation and, in some highly, weathered soils ionic strength induced adsorption were proposed as possible mechanisms for the reduction of exchangeable and solution Al (Pavan et al., 1987; Sumner et al., 1988).

Calcium exchange for H^+ and Al species, and SO_4^{2-} replacement of OH^- by ligand exchange, affect pH. In highly weathered soils, these opposing processes are often nearly balanced owing to relatively large quantities of hydroxylated surfaces on sesquioxides available for ligand exchange, as well as a low cation exchange capacity and therefore low exchangeable acidity (Shainberg et al., 1989).

Phytotoxic Al levels inhibit root growth by disrupting root cell division during mitosis. Root proliferation, as determined by root sampling and water extraction patterns, corresponded with soil zones where Al levels were reduced (Pavan et al., 1987; Sumner et al., 1988). Crop increases in phosphogypsum amended soils were apparently related to reduced phytotoxic Al levels and associated root proliferation rather than phosphogypsum induced changes in pH.

The dissolution rate of phosphogypsum partially controls its effectiveness as an amendment on acid soils and other problem soils. Factors which influence the dissolution rate include particle size, formation of a P and Al enriched skin on phosphogypsum granules, and the method of application. Coarse particles and skins can reduce the dissolution rate and the ameliorative effect of phosphogypsum (Frenkel et al., 1989b). Surface application of phosphogypsum was found to have a less beneficial effect on alfalfa yields and Al-Ca exchange reactions than deep incorporated lime (Sumner et al., 1986).

5.3. Reclamation of sodic soils

Sodic soils often exhibit poor soil structure due to the dispersion of clay particles that occur when high levels of sodium are present on the exchange complex of soils. The large, highly hydrated Na cation is less effective than smaller, divalent Ca ca-

tions at satisfying negative charges on clay surfaces; therefore, the replacement of Na with Ca reduces dispersion and promotes flocculation of soil particles. Phosphogypsum is an effective ameliorant for sodic soils because it supplies sufficient Ca to displace Na from the exchange complex of soils. Also, it has a relatively rapid dissolution rate and a relatively high solubility (Merrill et al., 1980; Okorkov, 1988; McKenzie and So, 1989a; Orlov et al., 1989).

Rates of phosphogypsum applied to sodic soils have been based on replacing a portion of the initial content of Na with an equivalent quantity of Ca. A coefficient of gypsum utilization for the displacement of Na has also been included in rate calculations (Okorkov, 1988). The gypsum utilization coefficient considers the factors which affect the efficiency and rate of Ca displacement of exchangeable Na. The percentage of Ca that exchanges for adsorbed Na will be much greater at high exchangeable Na levels (Shainberg et al., 1989).

Phosphogypsum applied at rates between 2.5 and 30 t ha^{-1} induced replacement of exchangeable Na with Ca (Merrill et al., 1980; Petrov and Savchenko, 1986; Okorkov, 1988; McKenzie and So, 1989a) and resulted in significant reductions in the pH of alkaline, saline, and saline-sodic soils (Mishra, 1980; Orlov et al., 1989). The flocculating effect of Ca on soil particles was found to decrease bulk density, increase porosity, and promote formation of soil structure and aggregate stability (Orlov et al., 1989). These changes in soil physical properties generally enhanced water infiltration and leaching of Na. The amount of infiltrating water, texture and initial hydraulic conductivity of soils were factors reported to affect the extent of leaching.

5.4. Erosion control

Erosion control studies have investigated the interrelated effects of phosphogypsum, precipitation and slope characteristics on soils which exhibit a tendency to disperse and form crusts. These soils are characterized by having high sodicity at the surface, or by containing highly weathered, non-sodic kaolinitic and illitic clays which disperse when water with a low electrolyte concentration is applied (Agassi et al., 1985, 1986, 1990; Miller, 1987; Stern et al., 1991). In general, crusting reduces infiltration and increases runoff and soil loss.

The dispersion process is due, in part, to a chemical mechanism which depends on the exchangeable sodium percentage and the electrolyte concentration of the applied water. The dispersed clay particles may be deposited in the upper few millimeters of the soil (Gal et al., 1984; Frenkel et al., 1989a) or are carried off as sediment in runoff. A second complementary mechanism involves the physical disintegration of surface aggregates under raindrop impact (Stern et al., 1991). When water of high electrolyte concentration is used, chemically induced dispersion is largely prevented and a thin seal with high permeability is formed, mainly by the physical mechanism (Agassi et al., 1985; Frenkel et al., 1989a).

Phosphogypsum application to soil mainly affects the dispersion process by rapidly introducing electrolytes including Ca, into the applied water at the soil surface. This promotes flocculation, enhances aggregate stability and deposition of entrained particles in runoff (Warrington et al., 1989; Agassi et al., 1985, 1990; Agassi and Ben-Hur, 1991). However, phosphogypsum may also inhibit physical disintegration by acting as a mulch to intercept and reduce the impact of raindrops. In general, application of phosphogypsum increases infiltration, decreases runoff, and decreases soil loss compared to control treatments.

The relative effectiveness of phosphogypsum for reducing erosion is partially dependent on the impact energy of rainfall at the soil surface (Smith et al., 1990). Other factors include slope gradient and length, application rate and method, and other agronomic practices. Agassi et al. (1990) found that the beneficial effect of phosphogypsum was less pronounced when the impact of raindrops decreased. The capability of phosphogypsum to supply sufficient electrolytes to inhibit dispersion during storms depends on the amount, intensity, and duration of rainfall of preceding storms (Stern et al., 1991). Agassi et al. (1985) reported that phosphogypsum reduced runoff by 76% compared

with control treatments, even after 528 mm of rainfall. In another study, beneficial effects lasted until the cumulative rain exceeded 700 mm (Stern et al., 1991). This long lasting effect is partially due to return of some of the gypsum to the soil surface through capillary rise during drying periods.

Soil loss increases with increased slope gradient. Runoff and soil loss has been reported to be less in phosphogypsum amended versus control treatments when the slope gradient increased (Agassi et al., 1985, 1989; Warrington et al., 1989). The difference in runoff between the phosphogypsum and the control treatments decreased as the slope increased. Apparently, the greater amount of erosion on control plots removed seal material which led to enhanced infiltration and decreased runoff as the slope increased (Agassi et al., 1985; Warrington et al., 1989).

A single, broadcast application of phosphogypsum at 5 t ha^{-1} was considered to be the most effective amendment in terms of water use efficiency; although a phosphogypsum broadcast at a rate of 10 t ha^{-1} resulted in the greatest cumulative infiltration and final infiltration rate. The effectiveness of phosphogypsum in preventing crust formation is reduced when it is incorporated; however, broadcasting phosphogypsum as a fine powder may expose it to wind erosion (Agassi et al., 1985).

Phosphogypsum has been compared to other amendments and agronomic practices designed to improve soil physical properties. Mulching with corn stover (3 t ha^{-1}) (Stern et al., 1991), straw (80% cover) (Frenkel et al., 1989a), and spray applications of polyacrylamide solution helped prevent physical disintegration of aggregates and were found to be more effective for controlling runoff than was phosphogypsum. The combined application of phosphogypsum and polyacrylamide had a synergistic effect on reducing runoff (Smith et al., 1990; Stern et al., 1991). Phosphogypsum was more effective in reducing runoff and erosion in potato fields than a diked furrow tillage treatment (Agassi et al., 1989). Fuel consumption, an indication of the ease of tillage, was reduced for disking and weeding operations following a 7.5 t ha^{-1} application of phosphogypsum (McKenzie and So, 1989b).

6. Environmental concerns related to the agricultural use of phosphogypsum

6.1. Radionuclide uptake by plants and radioactive buildup in soil

Radionuclides have been reported to be taken up by agricultural plants from soil contaminated by uranium processing wastes (Tracy et al., 1983) and mined phosphate lands (Guidry et al., 1986, 1990); hence, there is some concern that the application of phosphogypsum to agricultural lands may result in the uptake of radionuclides by food crops. Radionuclide uptake is influenced by soil factors and the type of plant species. Root crops, leafy vegetables and legumes tend to take up more radionuclides than fruit bearing plants (Tracy et al., 1983; Guidry, 1986).

Only a few studies have reported the radionuclide uptake by plants grown on phosphogypsum amended soils. May and Mordvedt (1986) applied up to 112 mg ha^{-1} of phosphogypsum containing 925 Bq kg^{-1} of Ra-226 to soil which was used to grow corn, wheat, and soybeans in rotation. No increases in grain Ra-226 were detected in any of the crops, although levels in the surface soil were increased from 35 Bq kg^{-1} to 73 Bq kg^{-1}. Arkhipov et al. (1984) found that rates up to 20 t ha^{-1} increased soil levels of radionuclides, but uptake and accumulation of radionuclides in wheat grain was only slightly higher than in control treatments. In another study, radioactivity determinations of sugarcane juice showed no significant difference in counts among background, control, and phosphogypsum treated areas (Golden, 1983). Relatively low application rates ($<$293 kg ha^{-1}) had little, if any, effect on Ra-226 and Po-210 levels in forage and soil samples (Mullins and Mitchell, 1990). Radium-226 and Pb-210 have been found to be significantly increased in plants grown on reclaimed phosphate mine lands (Guidry et al., 1990). However, the total radionuclide content in the root zone of these soils was at least an order of magnitude greater than what would be contained in a very heavy phosphogypsum application (i.e., 100 t ha^{-1}). It was estimated in the study by Guidry et al. (1990) that a person who obtained all of his or her leafy

vegetables, root vegetables, peas and beans from the phosphate mined lands would receive an effective dose equivalent of 19.1 mrem/year which is not considered to be a health hazard.

A few authors have conducted theoretical radiological assessments of radionuclide buildup in soil and uptake by plants from phosphogypsum applications. Lindeken (1980) described a scenario where phosphogypsum of 0.56 Bq g^{-1} Ra-226 content was applied to soil at an initial rate of 10 tons $acre^{-1}$ followed by alternate year applications of 5 tons $acre^{-1}$. If all the Ra-226 remained in the surface 6 inches, the proposed federal concentration limit of 0.19 Bq g^{-1} soil (federal concentration limit to lands contaminated by uranium tailings on which residences may be constructed) would not be reached for 100 years. Assuming a concentration ratio (radium in dry foodstuff to radium in soil) of 0.01 for crops growing on land containing 0.19 Bq Ra-226 g^{-1} soil, and assuming human consumption of 80 g day^{-1}, the integrated 50-year radiation dose to the bone would be 1.4 rem. The allowable annual dose for unrestricted persons is approximately 2 rem (Lindeken, 1980). It should be noted that the National Council of Radiation Protection (NCRP, 1984) guideline for restricting soil for the use of growing human food crops is a Ra-226 content of 1.5 Bq g^{-1} soil.

Roessler (1988) conducted a detailed radiological assessment to evaluate the extent to which the radioactivity originating from phosphogypsum applied to soil would appear in crops and contribute to human radiation exposure. In one scenario, phosphogypsum containing 1.1 Bq g^{-1} Ra-226 was applied at a rate of 1 ton $acre^{-1}$ once every 4 years and tilled to a depth of 15 cm. Assuming a 2% loss of Ra-226 from the root zone per year by erosion or leaching the equilibrium application concentration would be 0.014 Bq g^{-1}, which would be 90% of that attained after 100 years. Roessler (1988) assumed a very conservative concentration ratio of 1 but placed an upper concentration of 9 Bq Ra-226 kg^{-1} grain dry matter based on earlier observations with other Ra-226 bearing materials. Typical values for U.S. grain products are 0.081–0.093 Bq kg^{-1} (McDowell-Boyer et al., 1979). A person whose sole source of consumed grain products originating from food grown on phosphogypsum-treated land would consume approximately 1.9 Bq day^{-1} of Ra-226 and would receive a bone surface dose of 300 mrem $year^{-1}$ and a committed effective dose equivalent (CEDE) of 20 mrem $year^{-1}$. This intake level is about 50 times greater than the typical dietary uptake and 2.5 times greater than the Federal Radiation Council guidance. The 20 mrem $year^{-1}$ CEDE is 20% of the NCRP recommendation for continuous exposure to an individual of the general public. Roessler (1988) went on to say that these projected intakes and doses are significant but are probably overestimated because it is unlikely that total grain product intake would originate from phosphogypsum treated land. Also, high values were chosen with respect to Ra-226 concentration in plants, intake and dose. It was concluded that the proposed application of phosphogypsum to soil used for grain production would not pose a problem for tens of years although it would be difficult to extrapolate beyond 50 years because some factors were not well defined.

One important factor in the use of phosphogypsum on agricultural lands is the possibility of raising the overall radioactivity of the soil such that it becomes unsuitable for other uses. Thus, even though crops may be consumed from lands treated with phosphogypsum, the land may become unsuitable for residential use due to the potential radon risk in basements. Lindeken (1980) determined that a Ra-226 concentration of 0.19 Bq g^{-1} soil would generate radon daughter concentrations which exceed proposed guidelines for residential occupancy. May and Mordvedt (1986) raised soil Ra-226 from 0.035 to 0.073 Bq g^{-1} after one heavy application of phosphogypsum, thus a few more applications at these high rates would likely result in the guideline levels being exceeded. Recently the U.S. E.P.A. ruled that phosphogypsum would only be permitted for use in agriculture if the average concentration of Ra-226 in the phosphogypsum does not exceed 370 Bq kg^{-1} (Federal Register, 1992). This limit was set to assure that the risks due to indoor radon and direct gamma radiation in residences constructed on land previously treated with phosphogypsum do not exceed an acceptable level.

6.2. Non-radioactive element uptake by plants

The potential uptake of fluoride and trace elements derived from phosphogypsum are potential environmental concerns. Phosphogypsum applications of 10 or 20 t ha^{-1} did not result in accumulation of high fluoride concentrations in soil and plants (Petrov and Savchenko, 1986). Even if phosphogypsum application rates are large enough to cause high fluoride concentrations in the soil, some acid soil studies have shown or suggested that most of the fluoride would be adsorbed in the topsoil (Shainberg et al., 1989; Alva et al., 1990). Few studies have examined heavy metal uptake by plants from phosphogypsum treated soil. May and Mortvedt (1986) reported that very high rates of phosphogypsum application did not have any effect on Cd uptake in a corn-wheat-soybean cropping sequence, however, the Cd concentration of the phosphogypsum was only 0.23 $\mu g\ g^{-1}$. Typical soil levels are 0.35 $\mu g\ g^{-1}$ (Sposito, 1989).

6.3. Other concerns

Phosphorus contamination of surface waters as a result of land application of phosphogypsum is also a concern regarding the agricultural use of phosphogypsum. The results of a laboratory rainfall simulator study suggested that application of high phosphogypsum rates may result in P being exported into waterways adjacent to the sites of application and hence it may contribute to the enhanced eutrophication of the waterways (Korentajer et al., 1991).

7. Conclusions

Very large quantities of phosphogypsum have been produced world-wide since the 1950s because of the high demand for phosphate fertilizer, and because the wet phosphoric acid process produces about 5 tonnes of phosphogypsum for every tonne of phosphoric acid manufactured. Most of the phosphogypsum produced world-wide is stockpiled. Much interest has focused on finding uses for this by-product, such as a soil amendment for the remediation of problem soils. There are still unanswered questions about the environmental implications associated with the storage and agricultural use of phosphogypsum.

The main environmental concerns related to the storage and agricultural use of phosphogypsum are summarized in Fig. 3. Research has determined that acidity, F^-, SO_4^{2-}, certain trace elements and certain radionuclides may be elevated in the waste product and have the potential to be mobile in the environment. Both the acidic process water and the phosphogypsum itself are potential sources of contamination. Much concern is related to the possible contamination of groundwater under phosphogypsum stacks, and to radon exhalation which may pose a health risk to people working on or living close to a stack. Atmospheric F^- can be a significant contaminant from phosphate fertilizer manufacturing; however, most process plants use scrubbers to reduce gaseous F^- levels to within acceptable levels. Some authors predict that employees working on phosphogypsum stacks are at low risk from direct gamma radiation originating from the stacks, or from inhalation of phosphogypsum dust under normal weather conditions. The largest concern related to the use of phosphogypsum as an amendment to agricultural soils is not plant uptake of radionuclides but the risk of elevated indoor radon levels if the agricultural land is later converted to residential usage. For this reason the U.S. E.P.A. has ruled that no phosphogypsum may be used as a soil amendment if its Ra-226 content exceeds 370 Bq kg^{-1}.

The leachate chemistry of the radionuclides is of major importance in determining the environmental impact of phosphogypsum. It is generally believed that most Ra-226 in phosphogypsum exists as a sulfate compound in solid solution with Sr and Ba, however, the physical location of Ra-226 is not clearly resolved. Moisset (1988) found distinct crystals very rich in co-crystallized Ra-226, but some Ra-226 might also be present within the small quantities of hemihydrate that are contained in dihydrate phosphogypsum. Further clarification of the chemical form and physical location of Ra-226 in phosphogypsum may help explain its chemical behavior (Rutherford et al., 1994).

Although Ra-226 is considered to be the main source of radioactivity in phosphogypsum, other U-238 series radionuclides may be present in signi-

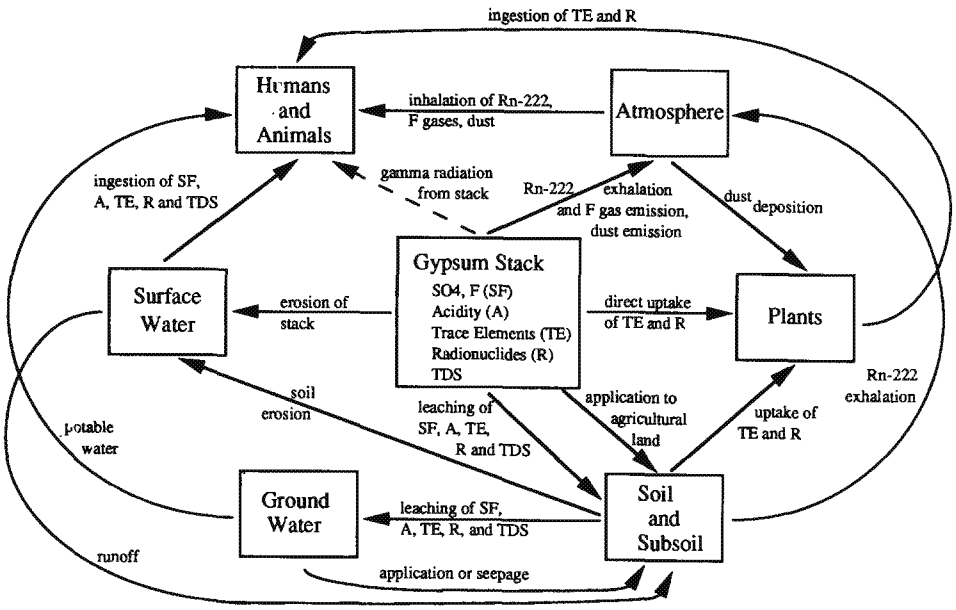

Fig. 3. Main environmental concerns due to the storage and agricultural use of phosphogypsum.

ficant quantities (Table 5). Alpha emitting radionuclides are more of a concern than beta emitters because they do more biological damage once they are inhaled or ingested. Uranium content in phosphogypsum can be quite variable, depending on phosphoric acid plant conditions. Some references have reported U-238 activities equal to that of Ra-226. This is a concern because U(VI) can be highly mobile in the environment. Polonium-210 is a relatively long-lived radionuclide (138 days) which is partitioned into phosphogypsum during the wet phosphoric acid process. Few studies have reported Po-210 chemistry in phosphogypsum, even though it has been found to be the major alpha emitting radionuclide in groundwater under phosphate mined lands. The chemistry of Po-210 is not clearly understood (Upchurch et al., 1991) and therefore requires further investigation. Practices which increase the carbon content and/or biological activity in phosphogypsum, such as the establishment of soil and vegetation caps on stacks, may increase radionuclide mobility due to the production of microbial chelating agents (Birch and Bachofen, 1990). Further research is required to elucidate radionuclide behavior in phosphogypsum and in phosphogypsum-treated soil.

The exhalation of Rn-222 from phosphogypsum stacks may vary by several orders of magnitude, ranging from <0.004 to >3 Bq m^{-2} s^{-1}. Because the U.S. E.P.A. recently adopted an average 0.74 Bq m^{-2} s^{-1} upper limit on Rn-222 emissions from phosphogypsum stacks it is important for companies to monitor their stacks and be aware of the variables which affect Rn-222 exhalation. Most studies have concluded that populations living close to phosphogypsum stacks are not subjected to a significant health risk because air movement readily dilutes Rn-222 concentrations. It is still not clear whether employees who spend numerous hours on active phosphogypsum stacks are subjected to a significant health risk. There is not much published literature on the effects of soil caps and vegetation cover on the release of Rn-222 from phosphogypsum surfaces.

There have been some inconsistent reports

regarding the mobility of phosphogypsum constituents. Some laboratory studies have concluded that significant levels of contaminants do not leach from phosphogypsum, however some field studies have found elevated levels of F^-, SO_4^{2-}, acidity, trace elements, radionuclides and total dissolved solids in groundwater near phosphogypsum stacks. Clearly, further research is required to improve our understanding of the geochemistry occurring within, and beneath, phosphogypsum stacks. To accomplish this it is necessary to identify the solubility-controlling solids of the elements contained within phosphogypsum, especially those for trace elements and radionuclides (Eary et al., 1990). It is also necessary to determine which conditions (e.g. redox, pH and ionic strength) exist within, and beneath, phosphogypsum stacks in order to predict the dominant chemical species present. It is also important to identify the reactions which occur when contaminants originating from phosphogypsum contact soil materials to determine if attenuation occurs before chemical species contact groundwater.

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Message

From: Lee, Raymond [Lee.Raymond@epa.gov]
Sent: 10/6/2020 2:10:11 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: 10014-36-OAR: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)

Hi all,

Ex. 5 Deliberative Process (DP)

Let me know if you have any questions.

Thanks,

Ray

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Tuesday, October 06, 2020 10:05 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: FW: 10014-36-OAR: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)

FYI

From: Franks, Martin <Franks.Martin@epa.gov>
Sent: Tuesday, October 06, 2020 9:58 AM
To: Manibusan, Mary <Manibusan.Mary@epa.gov>
Cc: Walker, Sherri <Walker.Sherri@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: 10014-36-OAR: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)

Edits Attached.

Ex. 5 Deliberative Process (DP)

Presently I submitted to Jonathan Walsh by FR Dailies.

Martin V. Franks

Federal Register Liaison
Regulatory Management Division
Environmental Protection Agency
Washington, DC 20460

Tel. 202-564-1172

From: Manibusan, Mary <Manibusan.Mary@epa.gov>
Sent: Tuesday, October 6, 2020 8:46 AM
To: Franks, Martin <Franks.Martin@epa.gov>
Cc: Walker, Sherri <Walker.Sherri@epa.gov>
Subject: FW: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)

Martin,

Can you please review this FRN (due COB today)? And send your comments to the program POC and cc me. I need to move this for signature.

Thank you!
Mary

From: Mcquilkin, Wendy <Mcquilkin.Wendy@epa.gov>
Sent: Monday, October 5, 2020 10:05 AM
To: Walker, Sherri <Walker.Sherri@epa.gov>; Rivera, Reiniero <Rivera.Reiniero@epa.gov>
Cc: ORIAREGPROCESSING <ORIAREGPROCESSING@epa.gov>; Campbell, Ann <Campbell.Ann@epa.gov>
Subject: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)

TO: OP/SHERRI WALKER/REY RIVERA FOR REVIEW AND SUBMITTAL FOR THE ADMINISTRATOR'S SIGNATURE.

Attached is the TFI Petition

RAY LEE
202 343-9463

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 10/6/2020 2:02:14 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: FW: FR Dailies - OP has concluded review on a OAR PKI document:Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute

Importance: High

FYI

From: Martin Franks <Franks.Martin@epamail.epa.gov>
Sent: Tuesday, October 06, 2020 9:50 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Brooks, Patricia <Brooks.Patricia@epa.gov>; Martin Franks <Franks.Martin@epamail.epa.gov>
Subject: FR Dailies - OP has concluded review on a OAR PKI document:Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute
Importance: High

OP has concluded review on a FR Dailies OAR PKI document
Title: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute

FRL #: 10014-36-OAR
Stage: Notice

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 12/4/2019 6:53:52 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: Subpart R history

3 should be fine. Thanks.

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, December 04, 2019 1:53 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Subpart R history

I'm about to walk in to a meeting. Do you want me to call around 3, or would you prefer that I call tomorrow?

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Wednesday, December 4, 2019 1:47 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: Subpart R history

Give me a call when you have a chance – there's one more question I had for you. Ex. 6 Personal Privacy (PP)

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 9/8/2020 2:19:56 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
CC: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: Questions on Text; just need you to read one last time

Great thanks for your help Dan!

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Tuesday, September 8, 2020 10:11 AM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Cc: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Questions on Text; just need you to read one last time

Ex. 5 Deliberative Process (DP)

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Tuesday, September 08, 2020 9:43 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: Questions on Text; just need you to read one last time

Hi Dan,

Stef and I are finishing up the comms plan, and had two FAQs that just needed a final glance by you to make sure the text is ok. I've copied them into this email:

Ex. 5 Deliberative Process (DP)

Thanks,

Joe

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 8/31/2020 2:09:50 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
CC: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: FW: TFI Materials
Attachments: Action Memo TFI Petition Approval August 27 2020 FINAL DRAFT.docx; CQR072.pdf; FR Typesetting TFI_.pdf; Response to TFI- Letter PDAA to TFI 08272020 FINAL DRAFT.docx; TFI Approval Action Information Form 8-27-2020 FINAL.doc; TFI FR_Notice_of_availability_Aug 27 FINAL DRAFT (needs cites).docx; TFI_Approval_1-pager_8-27-2020 FINAL DRAFT.docx

Joseph Rustick
Physical Scientist
Radiation Protection Division
Office of Radiation and Indoor Air
Office of Air and Radiation
U.S. Environmental Protection Agency
(202)-343-9682

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Friday, August 28, 2020 10:18 AM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: FW: TFI Materials

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, August 27, 2020 7:24 PM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Cc: Starrs, Charles <Starrs.Charles@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: TFI Materials

Hi Jon and Andrea,

We are nearing completion of the approval letter and the Federal Register package of materials for the TFI response. I am attaching review copies here for you. **Ex. 5 Deliberative Process (DP)**

Ex. 5 Deliberative Process (DP)

In this email, you have the following:
--Action memo, Edwards to Austin
--FR Notice
--Approval Letter to TFI from Austin
--2 one-page action information sheets necessary as part of a FR package
--FR Typesetting request (just to keep the package in one place, you don't need to do anything with those two PDFs)

Ex. 5 Deliberative Process (DP)

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 8/27/2020 10:17:55 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
CC: Bacon, Stefanie [Bacon.stefanie@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]
Subject: Current status of Technical Review

Hi Tom,

Ex. 5 Deliberative Process (DP)

Best,

Joe

Message

From: Diaz, Charlene [diaz.charlene@epa.gov]
Sent: 10/16/2020 6:08:58 PM
To: Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Griggs, John [Griggs.John@epa.gov]; Clark, Mike S. [Clark.Michael@epa.gov]; Stafford, Andrea [Stafford.Andrea@epa.gov]; Wilds, Edward [Wilds.Edward@epa.gov]; Brozowski, George [brozowski.george@epa.gov]
Subject: Questions #1 - SMR Rulemaking and TFI Press Release Discussion with the Regions

Hello all,

Please find below questions from Chuck Hooper in preparation for the discussion on Monday.

Thanks,
Charlene

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator
Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

From: Hooper, Charles A. <Hooper.CharlesA@epa.gov>
Sent: Friday, October 16, 2020 12:26 PM
To: Diaz, Charlene <diaz.charlene@epa.gov>
Cc: Brozowski, George <brozowski.george@epa.gov>
Subject: RE: PLEASE READ: SMR Rulemaking and TFI Press Release Discussion with the Regions

Charlene,
Here are some questions regarding the TFI phosphogypsum Press Release/Communication Plan:

- Can you share a copy of the TFI Risk Analysis with the Regions?
    - Generally, how are radon and groundwater risk applied?
    - Is there any comparison in the TFI Risk Analysis for public risk from the material's current state in a stack versus that of a road base? [40CFR61.206(c)] I think the Communication Plan's "Messages" may be misapplying the use of the 3E-4 risk level from the 1992 FR notice in that this risk level was used to derive the radium-226 concentration for agriculture applications in 61.204, but not specifically for "other purposes", i.e. road base.
- The Communication Plan states, "The terms and conditions of the approval also require that EPA be notified in writing prior to the distribution and/or use of phosphogypsum for any government road project. Further, there are road design and construction limitations, site monitoring, record-keeping, public notification, and worker safety requirements included as part of the approval terms and conditions." Who is held as the responsible party if the terms and conditions are not properly followed?

- Assuming the Nuclear Regulatory Commission has determined that phosphogypsum does not meet their regulatory authority of "discreet radium"; wouldn't the phosphogypsum material still be subject to the approval and licensing (or registration) by the State Radiation Program?
- Was the Superfund program consulted? Does the misuse or abandonment of a road project subject the parties to Superfund liability?
- Are there any financial assurance requirements by any parties, if/when a road changes and the road base material is moved or exposed?

Chuck Hooper, CHP
Radiation Safety Officer
EPA Region 7
11201 Renner Boulevard
Lenexa, Kansas 66219
(913) 551-7271 office
Hooper.CharlesA@epa.gov

From: Diaz, Charlene <diaz.charlene@epa.gov>
Sent: Thursday, October 15, 2020 11:29 AM
To: Aquino, Marcos <Aquino.Marcos@epa.gov>; Bhesania, Amy <Bhesania.Amy@epa.gov>; Borries, Samuel <borries.samuel@epa.gov>; Perez, Natalia A. <Perez.Natalia@epa.gov>; Brozowski, George <brozowski.george@epa.gov>; Cooper, Artra <Cooper.Artra@epa.gov>; Davis, Amber <Davis.Amber@epa.gov>; Freed, Rachel <freed.rachel@epa.gov>; Generette, Lloyd <Generette.Lloyd@epa.gov>; Honnellio, Anthony <Honnellio.Anthony@epa.gov>; Hooper, Charles A. <Hooper.CharlesA@epa.gov>; Jablonowski, Eugene <jablonowski.eugene@epa.gov>; McAuley, Jim <mcauley.jim@epa.gov>; Merritt, Steven <Merritt.Steven@epa.gov>; Povetko, Oleg <Povetko.Oleg@epa.gov>; Richards, Jon M. <Richards.Jon@epa.gov>; Schulingkamp, Cristina <schulingkamp.cristina@epa.gov>; Snowbarger, Robert <Snowbarger.Robert@epa.gov>; Wagner, Christine <Wagner.Christine@epa.gov>; Laurita, Matthew <Laurita.Matthew@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Griggs, John <Griggs.John@epa.gov>; Clark, Mike S. <Clark.Michael@epa.gov>; Stafford, Andrea <Stafford.Andrea@epa.gov>; Wilds, Edward <Wilds.Edward@epa.gov>; Brozowski, George <brozowski.george@epa.gov>
Subject: PLEASE READ: SMR Rulemaking and TFI Press Release Discussion with the Regions

Hello all,

We are scheduling a meeting on Monday, October 19, 2020 to discuss the following topics with the Regions:

- SMR Rulemaking – Lee Veal
- TFI Press Release – Jon Walsh/Tom Peake (**Link to Press Release**: https://www.epa.gov/newsreleases/epa-approves-use-phosphogypsum-road-construction)

On the RPP Call on Tuesday, October 20, 2020, we currently have a special guest, Kathy Held, from NCRP presenting on the call; therefore we have decided to have an off schedule meeting with the Regions on **Monday, October 19, 2020 from 2:15pm EST to 3:00pm EST** to allow time to discuss these topics without any time constraints.

Attached to this email you will find the TFI Communications Plan, which has an extensive Q&A, which will probably address some of your questions. If not, in preparation for the meeting on Monday, please send me in advance any questions you may have regarding these topics.

I hope all of you are available to attend the meeting on Monday and I look forward to receiving your questions in advance. Please look for an invite, which will contain the call-in information and the MS Teams link.

If I have mistakenly left someone off of this distribution, please feel free to forward as you find appropriate.

Thank you in advance,
Charlene

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator
Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 8/26/2020 8:48:19 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]
CC: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]
Subject: Edits on the EPA TFI technical review
Attachments: Phosphogypsum_risk_technical_summary_full_Markup_8-26-2020 tp.docx

All,
I think you did a good job with the technical review document. I have a few edits and comments to get at clarity. A couple of comments that may need discussion are below.

Ex. 5 Deliberative Process (DP)

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 9/25/2020 1:40:31 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
CC: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]
Subject: Let's finalize the TFI technical review document and road abandonment document today, no later than Monday

All,
I think the TFI technical review and road abandonment documents are looking really good.

It looks like there is only a little cleanup left so there is not much left to do to finalize them.
Please try to get the last comments in today and go final later today or Monday at the latest.

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Nesky, Anthony [Nesky.Tony@epa.gov]
Sent: 10/16/2020 1:22:29 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
CC: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: Re: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute

Jon or his designate can simply reply directly to her. I would send her a link to the notice when it comes out.

Tony

Sent from my iPhone

On Oct 16, 2020, at 9:19 AM, Nesky, Anthony <Nesky.Tony@epa.gov> wrote:

Jon or

Sent from my iPhone

On Oct 16, 2020, at 9:11 AM, Bacon, Stefanie <Bacon.stefanie@epa.gov> wrote:

Tony,

How do we deal with these? Do we need to officially respond? Forward to Kati for awareness?

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Friday, October 16, 2020 9:06 AM
To: Lee, Raymond <Lee.Raymond@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: FW: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute

This appears to be a phosphate-related NGO. I'll leave notifications to the official channels.

From: ManaSota-88 <manasota88@comcast.net>
Sent: Thursday, October 15, 2020 7:34 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute

Dear Mr. Walsh,

Please advise ManaSota-88, Inc. of publication in the Federal Register or any proposed agency action or agency action on [EPA-

HQ-OAR-2020-0442; FRL–10014-36-OAR] Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.

Please send notification at the following email and mail address:

Manasota88@comcast.net

Glenn Compton - Chair
ManaSota-88, Inc.
419 Rubens Drive
Nokomis, Florida 34275
(941) 966-6256

Message

From: Lee, Raymond [Lee.Raymond@epa.gov]
Sent: 10/15/2020 9:27:28 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
CC: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: RE: EPA-2021-000305 Coordination Memo

Hi Lee,

Ex. 5 Deliberative Process (DP)

Thanks,

Ray

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, October 15, 2020 3:52 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

Hi,

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Thursday, October 15, 2020 3:30 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>

Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: FW: EPA-2021-000305 Coordination Memo

Hi Jon/all,

Ex. 5 Deliberative Process (DP)

Thanks,

Ray

From: Hamilton, Sabrina <Hamilton.Sabrina@epa.gov>
Sent: Thursday, October 15, 2020 3:21 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>; Marbury, Candice <Marbury.Candice@epa.gov>
Subject: FW: EPA-2021-000305 Coordination Memo

Ray,

This FOIA will be assigned to ORIA sometime today. Thanks

Sabrina Hamilton

Sabrina Hamilton
Air and Radiation Liaison Specialist
and FOIA Coordinator
Office of Air and Radiation
U.S. Environmental Protection Agency (EPA)
1200 Pennsylvania Avenue, N.W. (6101-A)
Washington, D.C. 20460
Tel: (202) 564-1083

From: Hamilton, Sabrina
Sent: Thursday, October 15, 2020 3:17 PM
To: Davis, Gail <Davis.Gail@epa.gov>; Ingram, Earl <Ingram.Earl@epa.gov>; Malloy, Marilyn <Malloy.Marilyn@epa.gov>
Cc: Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Marbury, Candice <Marbury.Candice@epa.gov>; Lubetsky, Jonathan <Lubetsky.Jonathan@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

Gail,

Yes, this is OAR's FOIA. Please assign. Thanks

Sabrina Hamilton

Sabrina Hamilton
Air and Radiation Liaison Specialist
and FOIA Coordinator
Office of Air and Radiation
U.S. Environmental Protection Agency (EPA)
1200 Pennsylvania Avenue, N.W. (6101-A)
Washington, D.C. 20460
Tel: (202) 564-1083

From: Davis, Gail <Davis.Gail@epa.gov>
Sent: Thursday, October 15, 2020 3:12 PM
To: Ingram, Earl <Ingram.Earl@epa.gov>; Malloy, Marilyn <Malloy.Marilyn@epa.gov>; Hamilton, Sabrina <Hamilton.Sabrina@epa.gov>
Cc: Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

Thank you Earl.

From: Ingram, Earl <Ingram.Earl@epa.gov>
Sent: Thursday, October 15, 2020 3:06 PM
To: Davis, Gail <Davis.Gail@epa.gov>; Malloy, Marilyn <Malloy.Marilyn@epa.gov>; Hamilton, Sabrina <Hamilton.Sabrina@epa.gov>
Cc: Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

Gail.

This is an office of Air and Radiation Request. You will need to check with them. The link to the FR Notice is below. EPA-HQ-OAR-2020-0442; FRL–10014-36-OAR

https://www.epa.gov/sites/production/files/2020-10/documents/federal_register_text_of_neshap_subpart_r_approval_tfi_request_other_use_phosphogypsum.pdf

---

From: Davis, Gail <Davis.Gail@epa.gov>
Sent: Thursday, October 15, 2020 3:02 PM
To: Malloy, Marilyn <Malloy.Marilyn@epa.gov>; Ingram, Earl <Ingram.Earl@epa.gov>; Hamilton, Sabrina <Hamilton.Sabrina@epa.gov>
Cc: Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>
Subject: EPA-2021-000305 Coordination Memo

This is a National FOIA Office Intake Coordination for the above-mentioned FOIA request. A copy of the request is attached. Please review the attachment to determine if the request has enough information for your office to process under the FOIA. Please reply with one of the options below and by filling-in the requested information **no later than 5:00 pm your time on the next working day**.

NFO Preliminary Intake Review

[ ] The request is not reasonably described – clock not started – See Regulations at 40 C.F.R. 2.102(c)
[ ] The request is reasonably described – clock started – request may need additional clarification
NFO Notes: I wasn't sure if OAR or OCSPP would have responsive records for the attached request. Your guidance is appreciated.

FOIA Program Preliminary Intake Coordination (please complete)

1. [ ] **The request is not reasonably described.** My FOIA Program does not have enough information at this time to identify and locate the records. I understand the NFO will schedule a conference call with the FOIA requester. Our Program would like to be a part of the call: YES [ ] or NO [ ]
   - What additional information is necessary to process this request? (e.g. subject matter, date range, internal or external correspondence):
   - If YES, point of contact from your Program to attend the call:
   - If YES, what are the preferred dates and times to attend the call:

2. [ ] **The request is reasonably described**. My FOIA Program has enough information at this time to identify and locate the records.
   a) [ ] Please assign to my FOIA Program - additional clarification may be handled by my program.
   b) [ ] We would like the NFO's assistance in seeking additional clarification. Please stop the clock and schedule a conference call with the FOIA requester. Our Program would like to be a part of the call: YES [ ] or NO [ ]
      - What additional information is necessary to process this request? (e.g. subject matter, date range, internal or external correspondence):
      - If YES, point of contact from your Program to attend the call:
      - If YES, what are the preferred dates and times to attend the call:

3. [ ] **The request does not relate to work in my program.** Please assign to another FOIA Program or agency.
   - Suggested FOIA Program/agency if known:

4. [ ] OPTIONAL: The request can be responded to, **in part,** with **publicly available** or **previously released records**. The records are available at: *[INSERT LINK HERE].* ***If the publicly available or previously released records fully respond to the request, then the Program Office should prepare the close out letter with information to assist the requestor in retrieving the requested records.***
5.
   - [ ] The enclosed records fully respond to the request; *OR*
   - [ ] The enclosed records partially respond to the request.

If you have any questions about this NFO Intake Coordination, please contact me.

Message

From: Lee, Raymond [Lee.Raymond@epa.gov]
Sent: 10/15/2020 9:24:17 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
CC: Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm
Attachments: Attachment A - Road Specs.pdf

Hi Stef,

Ahh, my apologies for the miswording/confusion – I have 9 appendices, plus the Attachment A of Road Specs. Not sure why I lumped them all together.

Just for reference, that attachment is tagged onto this e-mail.

Thanks,

Ray

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, October 15, 2020 3:47 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Hi Ray,

I compared the documents Ray listed as being added to the docket and the items Tony has posted to our supporting documents page. It looks like all documents listed on our web page have also been queued up to be on the docket. I only have one question:

Tony & Ray: Is there an additional TFI appendix? Ray mentioned 10 are in the docket. Our website has 9.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 2:29 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Ex. 5 Deliberative Process (DP)

So, Jon, when you send out the document in a few minutes, please include Charles on the distribution.
Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: Redacted

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Thursday, October 15, 2020 2:26 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Hi all,

All supporting documentation I've received (a total of 15 documents – the PG Risk Assessment Review [plus 10 appendices], the April TFI petition, 1992 BID, memo for road abandonment, and signed letter from the Administrator) has been processed and uploaded into the docket. Again, the number in regulations.gov is:

EPA-HQ-OAR-2020-0442

As Jon sent out to us, the FR will be published on 10/20. That's plenty of time for the docket staff to do their final QA, so there should not be any issues.

Let me know if I've missed anything or if there are any additional docs we need to have in there in the meantime.

Thanks again all,

Ray

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Thursday, October 15, 2020 11:55 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 11:50 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

And to Ray, so he can put it in the docket.

From: Schultheisz, Daniel
Sent: Thursday, October 15, 2020 11:32 AM

To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Can you send Tony the 1992 BID? We should probably put it on the web site.

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Thursday, October 15, 2020 11:31 AM
To: Peake, Tom <Peake.Tom@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

On it now.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 10:40 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: Please try to get the final edits/review of the technical review done by around 2 pm

Jon,

Ex. 5 Deliberative Process (DP)

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Lee, Raymond [Lee.Raymond@epa.gov]
Sent: 10/15/2020 9:19:47 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Yes it did!

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, October 15, 2020 3:59 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Ray,

Apologies for the second email, I know we have all seen more than enough emails for the day. Please confirm: Did TFI's original October petition get added to the docket? I was not sure if that was captured by your list below.

Thanks,
Stefanie

From: Bacon, Stefanie
Sent: Thursday, October 15, 2020 3:47 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

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Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
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Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Thursday, October 15, 2020 2:26 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

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Thanks again all,

Ray

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Thursday, October 15, 2020 11:55 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

---

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 11:50 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

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From: Schultheisz, Daniel
Sent: Thursday, October 15, 2020 11:32 AM

To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

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Sent: Thursday, October 15, 2020 11:31 AM
To: Peake, Tom <Peake.Tom@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

On it now.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 10:40 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: Please try to get the final edits/review of the technical review done by around 2 pm

Jon,

Ex. 5 Deliberative Process (DP)

There is a push to get everything loaded onto the web as soon as possible, so can you try to get the final technical review document in a revised Word document and in a pdf document by around 2 pm to us?

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Egidi, Philip [Egidi.Philip@epa.gov]
Sent: 8/13/2020 6:26:26 PM
To: Stuenkel, David [Stuenkel.David@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: Description of road previous road projects and references.
Attachments: Pub1582_web.pdf

Please see pp 147 – 150 for description of US road experiments.
The whole of Chapter 10 P 111) is informative, particularly with respect to soil amendments and fertilizer research and applications.
See ya at 2:00...
PVE

Philip Egidi
Environmental Scientist
U.S. Environmental Protection Agency
Radiation Protection Division
Washington, DC
(202) 343-9186 (work)
(202) 222-5612 (Work cell)
(970) 209-2885 (Personal Cell)

"When the going gets weird, the weird turn pro." – Dr. Hunter S. Thompson

Safety Reports Series

No. 78

Radiation Protection and Management of NORM Residues in the Phosphate Industry

IAEA

International Atomic Energy Agency

ED_005285_00000684-00001

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RADIATION PROTECTION AND MANAGEMENT OF NORM RESIDUES IN THE PHOSPHATE INDUSTRY

ED_005285_00000684-00003

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SINGAPORE
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SYRIAN ARAB REPUBLIC
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THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
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TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
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UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
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VENEZUELA
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YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

SAFETY REPORTS SERIES No. 78

RADIATION PROTECTION AND MANAGEMENT OF NORM RESIDUES IN THE PHOSPHATE INDUSTRY

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2013

ED_005285_00000684-00005

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Includes bibliographical references.

1. Phosphate industry — Waste disposal. 2. Radiation — Safety measures. I. International Atomic Energy Agency. II. Series.

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FOREWORD

The Fundamental Safety Principles (IAEA Safety Standards Series No. SF-1), together with Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (IAEA Safety Standards Series No. GSR Part 3 (Interim)), set out the principles and basic requirements for radiation protection and safety applicable to all activities involving radiation exposure, including exposure to natural sources of radiation. The Safety Guides on Occupational Radiation Protection in the Mining and Processing of Raw Materials (IAEA Safety Standards Series No. RS-G-1.6) and Management of Radioactive Waste from the Mining and Milling of Ores (IAEA Safety Standards Series No. WS-G-1.2) provide guidance on the control of exposure of workers and members of the public to naturally occurring radioactive material (NORM) in industrial activities involving the exploitation of minerals. This guidance applies irrespective of whether the minerals are exploited for their radioactivity content. The phosphate industry constitutes one of several industry sectors for which the radioactivity content of the minerals and raw materials involved is large enough to warrant consideration by the regulatory body concerning the possible need to control exposures of workers and members of the public.

This Safety Report has been developed as part of the IAEA's programme to provide for the application of its safety standards in the field of radiation, transport and waste safety. It is a compilation of detailed information on the processes and materials involved in the phosphate industry and on the radiological considerations that need to be taken into account by the regulatory body when determining the nature and extent of radiation protection measures to be taken. This is consistent with the graded approach to regulation, in terms of which the application of the requirements of the safety standards is commensurate with the characteristics of the practice or source and with the magnitude and likelihood of the exposures.

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EDITORIAL NOTE

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1. INTRODUCTION

1.1. BACKGROUND

Phosphorus is an essential component of all living systems, such as nervous tissue, bone and cell protoplasm. Phosphorus is highly reactive and, therefore, is not found as a free element in nature. It occurs principally in rock deposits containing various mineralized forms of calcium phosphate, $Ca_3(PO_4)_2$, from which commercial phosphate, a non-substitutable, non-renewable resource, is derived on a large scale. The production of phosphate fertilizers and animal feeds constitutes the major commercial activity in the phosphate industry. Phosphorus compounds are also used in a wide variety of food, pharmaceutical, industrial and domestic products.

Phosphate deposits contain the naturally occurring radionuclides ^{238}U and ^{232}Th together with their decay progeny, more details of which are given in Appendix I. From the 1950s to the late 1990s, uranium was recovered as a commercial product in some phosphate processing facilities. Regardless of whether or not the ore has potential for uranium recovery, the presence of these radionuclides of natural origin creates a potential need to control exposures of workers and members of the public in accordance with IAEA safety standards (the Standards), in particular the Fundamental Safety Principles [1], Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (the BSS) [2], the Regulations for the Safe Transport of Radioactive Material [3] and other relevant Safety Guides [4, 5]. In some process materials, the activity concentrations of radionuclides in the ^{238}U decay series are such that, in terms of the Safety Guide on Application of the Concepts of Exclusion, Exemption and Clearance [6], these materials would be considered for inclusion within the scope of regulation, as naturally occurring radioactive material (NORM).

The Safety Report on Assessing the Need for Radiation Protection Measures in Work Involving Minerals and Raw Materials [7] confirms that the phosphate industry constitutes one of several minerals related industry sectors for which some of the processes involved may warrant radiation protection measures through the system of regulatory control for practices. Reference [7] emphasizes the particular relevance of the graded approach to regulation to ensure that any radiation protection measures applied to the industrial processes involved and to the management of NORM residues arising from those processes are commensurate with the characteristics of the operation and with the magnitude and likelihood of the exposures. This implies the need for a thorough understanding of all the processes, the process materials, the associated

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radiological risks to workers and to members of the public, and the practicalities of any protective measures that need to be considered.

Radioactivity in phosphate deposits has been a subject of study since the early 1900s, at which time it was already known that phosphate deposits contain uranium in concentrations that can be sufficiently high to be of potential value [8, 9]. The mining of phosphate ore, the processing of it into intermediate and end products and the handling and use of those products can all give rise to exposures of workers and members of the public. Residues associated with phosphate processing may also give rise to exposures. When phosphate rock is digested with acid to produce phosphoric acid (the primary starting point for the manufacture of several major phosphate products), some of the radionuclides, particularly isotopes of radium, become concentrated in residues, such as the scale that tends to form inside pipes and vessels. In high temperature processes, radioactive isotopes of the more volatile elements polonium and, to a lesser extent, lead become concentrated in the fume.[1] Hence, from a radiation protection point of view, process residues are potentially of greater concern than the feedstocks and products.

The production of phosphoric acid, phosphate fertilizer and phosphate animal feed can give rise to risks to human health and to the environment from non-radioactive constituents, notably fluorides and heavy metals, such as arsenic, cadmium, lead and mercury. In sufficient concentrations, fluorides can be toxic and environmentally detrimental. They may have to be removed from phosphoric acid and recovered as fluosilicic acid, which has no significant radioactivity content and is used in such applications as water fluoridation. In some instances, phosphate products may require appropriate management to ensure that the public and the environment are adequately protected against exposure to these non-radiological constituents. Radiological considerations are usually of secondary importance but may also have to be taken into account. A particular example in this regard is phosphogypsum, a co-product of phosphoric acid production that, because of the very large amounts involved, is stored in above-ground engineered containments known as 'stacks', often for indefinite periods, or is sometimes disposed of in surface water bodies such as estuaries and the sea. Best practices established for the management of non-radiological risks to humans and to the environment have generally proven to be effective in minimizing any risks arising from the residual radioactivity content. Nevertheless, the radioactivity aspect continues to arouse public concern in some countries.

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[1] The term 'fume' in this context denotes the vapour and/or suspended fine dust particles released from a high temperature industrial process.

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1.2. OBJECTIVE

The objective of this Safety Report is to provide detailed information that will assist regulatory bodies and industry operators in implementing a graded approach to the protection of workers and of members of the public against exposures arising from the processes and products associated with the phosphate industry. The information provided in this Safety Report will also serve as the basis for creating a common understanding, based on common knowledge, between the various stakeholders in the production of phosphate products, including the primary producers (the phosphate industry) and the regulatory bodies involved.

1.3. SCOPE

This Safety Report provides practical information on the radiological risks to workers and to members of the public in the production and use of phosphate based products, their assessment and their management based on the application of the appropriate Standards and good working practices. This information has been compiled from published literature, from unpublished data provided by contributors to this report and from numerous experts with extensive experience, notably in the various sectors of the phosphate industry. The report describes the basic industrial processes associated with the phosphate industry, from the mining of phosphate ore to the production and use of phosphate fertilizers, animal feeds, phosphogypsum and other products. For each process, the radiological parameters of the raw materials, products and residues are quantified, as well as the exposure levels for workers and for members of the public. The data are used as the basis for determining, in principle, the need for, and extent of, regulatory control to ensure that the requirements of the Standards for each aspect of the industrial processes involved are met. Information is provided on monitoring and dose assessment techniques, measures taken to reduce doses, the transport and storage of bulk raw materials and the management of the various waste streams. The report covers both routine operations and non-routine operations such as plant maintenance, decommissioning and decontamination.

1.4. STRUCTURE

Following this introduction, Section 2 provides an overview of the phosphate industry, covering the early history of phosphate fertilizer production, a description of phosphate resources, processes and products and a review of

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recent trends worldwide. Section 3 summarizes the radiation protection considerations that apply to NORM industries in general and the phosphate industry in particular, including the application of the Standards, the main exposure pathways involved, the monitoring of exposed workers and dose assessment, as well as providing an example of radionuclide migration during various stages of phosphate processing. Section 4 deals with the mining and beneficiation of phosphate ore, beginning with a description of the processes and process materials involved (including, in particular, the radionuclide concentrations), followed by data on the exposure of workers and members of the public and concluding with a discussion of the regulatory implications. This basic reporting structure — process description, radionuclide concentrations, occupational and public exposure, and regulatory considerations — provides a common framework for the sections that follow, starting with the production of phosphoric acid by acid digestion (Section 5) and then moving on to the manufacture and use of ammonium phosphate fertilizer (Section 6), superphosphate fertilizer (Section 7), nitrophosphate fertilizer (Section 8) and animal feed phosphates (Section 9). The storage, use and disposal of phosphogypsum, a co-product of phosphoric acid production, give rise to a variety of radiological (and non-radiological) considerations, and these are covered in Section 10. The decommissioning of plant and the recycling or disposal of contaminated scrap arising from maintenance or decommissioning are discussed generically in Section 11, the radiological considerations being, in principle, common to all the 'wet' chemical processes covered in the preceding sections. Recently, there has been a revival of interest in two additional processes in the phosphate industry that had fallen from favour over the years. These are the extraction of uranium from phosphoric acid, which is addressed in Section 12, and the production of elemental phosphorus by the thermal processing of phosphate rock, which is addressed in Section 13. Additional, more detailed, technical information is presented in six appendices covering the following topics: (i) radionuclides in the ^{238}U and ^{232}Th decay series, (ii) the composition of phosphate ores, (iii) phosphate products and their uses, (iv) the composition of (beneficiated) phosphate rock, (v) methods for converting phosphate rock into phosphoric acid using sulphuric acid attack and (vi) the composition of phosphogypsum. Finally, some additional information is provided in two annexes, one summarizing the particle size characterization of airborne dust in a phosphoric acid plant and related dissolution studies and the other describing the remediation of a coastal and marine phosphate residue deposit.

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2. OVERVIEW OF THE PHOSPHATE INDUSTRY

2.1. EARLY PHOSPHATE FERTILIZER PRODUCTION

The production of phosphate fertilizer has always been the primary activity of the phosphate industry and accounts for the vast majority of global phosphate production. Phosphate fertilizer technology was initially very simple. The use of dilute sulphuric acid was introduced to Bohemia in 1831 to convert biogenic phosphate in the form of bones and coprolites[2] to a largely water soluble form. The product was called superphosphate, a term already used by chemists and apparently first used as early as 1797 by the British physician George Pearson to describe the phosphate compound calcium dihydrogenphosphate ($Ca(H_2PO_4)_2$) found in bone. In 1840, Justus von Liebig made a historic address before the British Association of Science in which he gave a clear exposition of the role of minerals in plant growth and laid the groundwork for modern agricultural science. He was the first to demonstrate scientifically that insoluble phosphates such as bone could be made to release their phosphorus in a form more quickly available to growing plants if they were caused to react with sulphuric acid. That suggestion stimulated John Bennett Lawes to treat coprolites with sulphuric acid and to test the resultant phosphate as a plant nutrient. (Coprolites were a fairly abundant source of phosphorus in the United Kingdom at that time.) In 1842, Lawes was granted a patent on this idea, which permitted him to establish the first commercial superphosphate works. Within 20 years, the United Kingdom was producing 150 000 t of superphosphate per year [10].

In the early stages of the industry, bones from European battlefields, along with cattle bones from the Russian Federation and South America, were popular sources of biogenic phosphates. Surging demand for phosphate led to the extensive export from Peru of guano, a rich source of phosphate. The rapid growth of world demand for phosphate in the 1850s severely depleted these known resources of bones, coprolites and guano [11–13].[3] It was the exhaustion of these and other biogenic sources of supply that acted as a catalyst to the emergence of the modern phosphate industry. The supply of phosphate was eventually secured by the discovery of large sedimentary phosphate deposits, known as phosphorite, in South Carolina, United States of America. Mining began in 1867. By 1870, several deposits of phosphorite were being exploited to supply rock to the growing superphosphate industries of Europe and America and

[2] Coprolites are fossilized animal faeces.

[3] By 1851, the United Kingdom was the major importer of bones for bone meal.

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bones and coprolites were rapidly supplanted. The estimated market value had grown by that time to some £8 million (1870s values) [14]. By 1889, the South Carolina mine was supplying 90% of the worldwide phosphate industry. At about the same time, prospecting was active in Florida, United States of America, in the search for new sources of commercially exploitable rock [13].

2.2. PHOSPHATE RESOURCES

Phosphate deposits contain calcium and phosphorus, essentially as tricalcium phosphate, $Ca_3(PO_4)_2$, and fall into five major categories:

(i) Sedimentary marine deposits;
(ii) Igneous (magmatic) deposits;
(iii) Metamorphic deposits;
(iv) Biogenic deposits, mainly accumulations of bird and bat guano;
(v) Deposits caused by weathering.

Most phosphate deposits are of a single type, although a few, including some recent discoveries, are mixtures of sedimentary and igneous types. Sedimentary marine deposits account for the majority of worldwide phosphate production [15]. This market dominance is expected to continue in the future. Such deposits originate from the sedimentation of bones of fish and marine mammals and are normally found in layers. Being of animal origin, they commonly contain impurities because non-phosphate components of animal bodies are also deposited with the phosphate-containing portions. Some very old marine deposits are associated with fossils [12]. Igneous deposits, which account for most of the remaining worldwide phosphate production, are created by magmatic extrusion in the form of an alkaline chimney, usually with a roughly circular cross-section, and are relatively inhomogeneous. They tend to contain fewer impurities than sedimentary phosphates and are generally free of organic material.

Phosphate ores contain one or more phosphate minerals suitable for commercial use, such as calcium fluophosphate. The mineralogy of phosphorus rich rocks is complex and there are more than 200 known phosphate minerals. The main mineral group is the apatite group of calcium phosphates having the general chemical formula $Ca_{10}(PO_4,\pm CO_3,\pm OH)_6(OH,F,Cl)_2$. The exact chemical composition varies with origin. Apatites are found mainly in sedimentary, metamorphic and igneous rocks and include fluorapatite, hydroxyapatite, carbonate-hydroxyapatite and francolite.

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Fluorapatite is described by the chemical formula $Ca_{10}(PO_4)_6F_2$ (alternatively expressed as $3Ca_3(PO_4)_2 \cdot CaF_2$) or $Ca_{10}(PO_4)_6(F,OH)_2$. It is found mainly in igneous and metamorphic environments, such as in carbonatites and mica pyroxenites. Pure fluorapatite contains 42% P_2O_5.[4]

Hydroxyapatite is described by the chemical formula $Ca_{10}(PO_4)_6(OH)_2$. It is found mainly in igneous and metamorphic environments but also in biogenic deposits such as bone deposits.

Carbonate-hydroxyapatite is described by the chemical formula $Ca_{10}(PO_4,CO_3)_6(OH)_2$ or $Ca_{10}(PO_4)_{6-x}(CO_3)_x(OH)_{2+x}$. It is found mainly on islands and caves as part of bird and bat excrement (guano).

Francolite is a commonly occurring complex carbonate-fluorapatite that exhibits several kinds of ionic substitution, principally CO_3F^- for PO_4^{3-} (which therefore reduces the phosphate content), Na^+ and Mg^+ for Ca^{2+} and perhaps OH^- for F^- [16]. Francolite has been described as two similar but distinct compounds [17] that may be represented in a consolidated form by the chemical formula $Ca_{10-a-b}Na_aMg_b(PO_4)_{6-x}(CO_3)_xF_yF_2$ where a = x–y and x = 0–1.5. The formula $Ca_{10-x-y}Na_{2x}Mg_y(PO_4)_{6-z}(CO_3)_zF_2F_{0.5z}$ has also been suggested. Francolite is found mainly in marine sedimentary environments and, to a much lesser extent, in weathered environments such as those covering carbonatites.

2.3. PHOSPHATE PRODUCTION AND RESERVES

Total global phosphate deposits are estimated to be 163 billion t. Most of these deposits are of sedimentary origin, with as little as 4% being of igneous origin [12]. Phosphatic materials are usually characterized in terms of their P_2O_5 content. This is done as a convenience and not as a strict chemical description. Phosphate ores generally have P_2O_5 contents in the range 4–40%. The fluorine content, which is associated principally with fluorapatite and francolite, varies from less than 1% to more than 4% and can be of concern if allowed to find its way into phosphate animal feed products or into the environment. Small amounts of heavy metals, which are potentially harmful to human health, are also found in phosphate ores. More detailed data on the composition of phosphate ores are given in Appendix II.

The concept of exploitability of phosphate deposits is subject to constant redefinition as mining and beneficiation techniques and technologies evolve, partly in response to market forces. A number of economic and technical factors

[4] Throughout this report, the percentage values used for quantifying chemical composition refer to weight per cent.

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influence quite significantly the calculation of phosphate reserves, not least the cost of processing rock with a relatively low phosphate content. For a phosphate deposit to be considered viable, the phosphate mineral component of the ore (that is, the phosphate rock remaining after removal of the barren material) must have a P_2O_5 content above a certain minimum value. The determination of this minimum value tends to be based on the suitability of the phosphate rock for digestion with acid to produce marketable phosphoric acid (the strength of which needs to be at least 28% P_2O_5). Historically, phosphate rock needed to have a minimum P_2O_5 content of 27–30%, but changes in manufacturing practice are now enabling some phosphate deposits to be categorized as ore reserves if the phosphate rock component has a minimum P_2O_5 content of 23% and, in some cases, even less [18]. Owing to the fact that early scientific research into phosphate recovery was conducted on bones, it is still common for the phosphate content of phosphate rock to be expressed in terms of a 'bone phosphate of lime' (BPL) number, where a BPL of 1 represents a P_2O_5 concentration of 0.4576%. Thus, phosphate rock with a P_2O_5 content of 30% (a typical value for commercial production of phosphoric acid) has a BPL of 66.

A breakdown of worldwide phosphate production and reserves, as reported in Ref. [19], is given in Table 1. In 2010, China, Morocco and the USA together accounted for almost two thirds of worldwide mining production of phosphate rock. The USA was historically the world's largest producer but was overtaken by China in 2006–2007. This was symptomatic of a more general trend towards increased phosphate mining outside the USA. At the same time, mining within the USA has been decreasing as a result of the combined effects of pricing policies and local public opposition to mining, especially in Florida, where most of the mining takes place. In 2008, Morocco announced that, in response to surging demand, it was planning to double its mining production, putting it within reach of becoming the future global leader in phosphate mining production.

2.4. PROCESSES AND PRODUCTS

Phosphate ore is converted into commercial products using the following three main process steps:

(i) After being mined, phosphate ore is beneficiated to produce a concentrate known as phosphate rock (also known as beneficiated phosphate rock or phosphate rock concentrate).
(ii) According to Ref. [20], as much as 85% of the phosphate rock produced in step (i) is converted into intermediate or final products using a process of

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TABLE 1. PRODUCTION AND RESERVES OF PHOSPHATE ROCK (BY COUNTRY) [19]

Country	Estimated mine production in 2010 (million t)	Reserves (million t)
China	65	3700
USA	26.1	1400
Morocco and Western Sahara	26	50 000
Russian Federation	10	1300
Tunisia	7.6	100
Jordan	6	1500
Brazil	5.5	340
Egypt	5	100
Israel	3	180
Syrian Arab Republic	2.8	1800
Australia	2.8	82
South Africa	2.3	1500
Algeria	2	2200
Togo	0.8	60
Canada	0.7	5
Senegal	0.65	180
Other countries	9.5	620
Total (rounded)	176	65 000

acid digestion known as the 'wet process'.[5] A relatively small amount is converted directly into elemental phosphorus by reduction in an electric arc furnace in a process known as the 'thermal process'. It is estimated that 71% of all phosphate rock produced is processed into phosphoric acid

[5] In some instances, finely ground phosphate rock, sometimes known as 'reactive phosphate rock', is applied directly to soil as a fertilizer, while 'partially acidulated phosphate rock' has been used in Australia and New Zealand, as well as in some developing countries where plant nutrient resources may be both scarce and unaffordable. It is estimated that the phosphate rock used in this manner accounts for only 0.3% of total phosphate rock production [21–23].

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(involving, in most cases, the co-production of large amounts of phosphogypsum), 24% is processed directly into fertilizer (as opposed to indirect processing via phosphoric acid) and the remaining 5% is converted directly into various other products. The annual production of P_2O_5 in the form of phosphoric acid is more than 30 million t.

(iii) Most of the phosphoric acid produced in step (ii) (estimates vary from 75% to 90%) is subjected to further chemical processing to convert it into fertilizer. The fertilizer products so derived from phosphoric acid thus account for some 55–60% of total phosphate rock production. Of the remaining 10–25% of phosphoric acid produced in step (ii), about half is processed into animal feed supplements and half into a variety of other products. The recovery of uranium from phosphoric acid (to which most of the uranium in the ore migrates) was an important activity prior to the slump in world uranium prices in the 1980s and 1990s. With the revival of interest in nuclear power and the depletion of uranium stockpiles, the recovery of uranium from phosphoric acid is set to increase once more.

An aerial view of a complete phosphate fertilizer production facility is shown in Fig. 1. The site illustrates many of the important social and environmental issues associated with such facilities. It is an environmentally sensitive area, close to a growing urban settlement that is gradually encroaching on the site. The facility has been in operation for over 50 years and now includes land recovered from the stockpiling of phosphogypsum. As part of the long term decommissioning process, this land is planned for redesignation as an amenity for the local community. In preparation for release, it has already been successfully replanted with selected native trees and shrubs.

A schematic view of the processes and products involved in the phosphate industry is shown in Fig. 2. An estimate of how the phosphate in the ore (expressed as P_2O_5) is distributed among the various process materials and products is given in Table 2. The amounts have been calculated by piecing together information from various sources and assuming, as a starting point, an annual phosphate rock production of 160 million t with an average P_2O_5 content of about 30% (66 BPL). Owing to changing circumstances and incomplete commercial data, Table 2 conveys only a general impression and is not intended to be definitive. Nevertheless, it can be concluded that some 80% of all exploitable P_2O_5 currently being extracted from the earth by phosphate mining is destined for use in fertilizer, while about 7% ends up in animal feed supplements. The remainder finds its way into a wide variety of products used in the food and beverage industry, in pharmaceutical and household products and in a diversity of industrial applications including:

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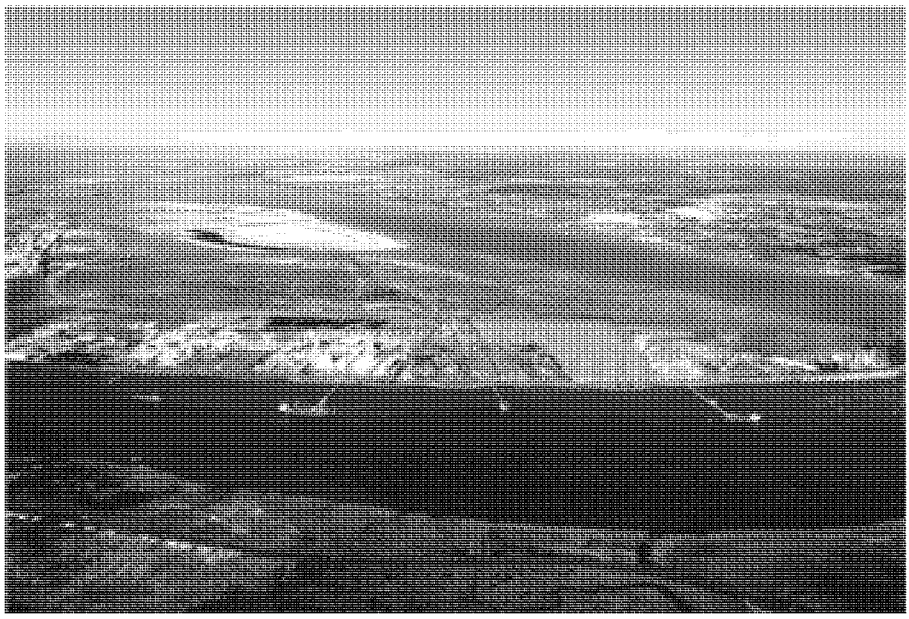

FIG. 1. A facility at Huelva, Spain, producing phosphate fertilizer from phosphate rock imported by sea. The associated phosphogypsum stockpiles (stacks) are visible in the background (courtesy: Fertiberia, Spain).

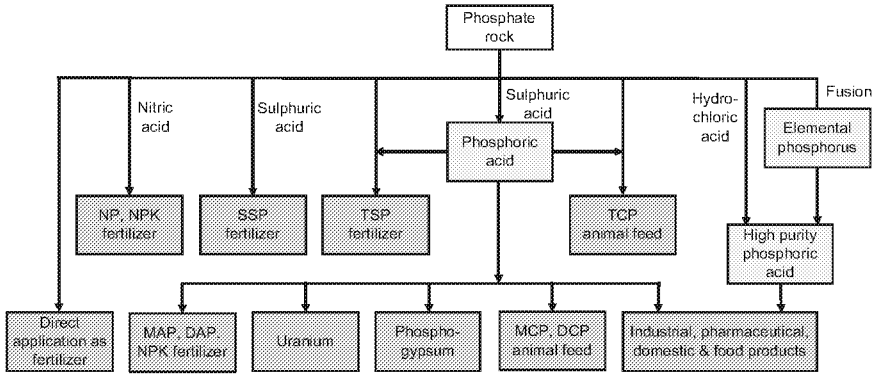

FIG. 2. Phosphate rock product streams. (NP: nitrogen–phosphorus; NPK: nitrogen–phosphorus–potassium; SSP: single superphosphate; TCP: tricalcium phosphate; TSP: triple superphosphate; MAP: monoammonium phosphate; DAP: diammonium phosphate; MCP: monocalcium phosphate; DCP: dicalcium phosphate)

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TABLE 2. DISTRIBUTION OF THE PHOSPHATE CONTENT OF THE ORE AMONG THE VARIOUS PROCESS MATERIALS AND END PRODUCTS

Material	Estimated amount of material generated annually worldwide (million t)		Exploitable P_2O_5 content as a proportion of that contained in the ore (%)
	Material mass	Mass of exploitable P_2O_5 content	
Ore[a]	530	48	100
Phosphate rock[a]	160	48	100
Tailings	370	0	0
Phosphogypsum	170	1.8	4
DAP fertilizer	41	20	41
MAP fertilizer	8	4.3	9
SSP fertilizer	23	6	13
TSP fertilizer	6	3.4	7
Other fertilizer	—	4.5	9
MCP–DCP animal feed	6	2.7	6
TCP animal feed	1	0.3	1
Other phosphate products	—	5	10

[a] It is recognized that there are significant deficiencies in the extraction of the exploitable content of the rock, leading to estimated losses of up to 30% of the P_2O_5 in the ore prior to beneficiation [24]. For the purposes of this table, these losses are not taken into account.

(a) The manufacture of chemicals, textiles, leather, glass, cement, ceramics, paper, rubber, electronic components and fire retardants;
(b) The treatment and coating of metals;
(c) Foundries;
(d) Water treatment;
(e) Mining and oil well drilling.

Many products comprise phosphates of sodium, potassium, calcium, ammonium and magnesium. A more detailed list of the various products associated with the phosphate industry is given in Appendix II. Products destined for human consumption via food, beverages or pharmaceutical products are required to meet strict purity requirements that limit the concentrations of heavy metals and fluoride, thereby ensuring also that radioactivity levels are well below

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levels of concern. An analysis of a typical product for human consumption (tricalcium phosphate) showed that the radionuclide concentrations were less than 0.05 Bq/g [25]. Consequently, such products are not discussed further in this report.

2.5. RECENT DEVELOPMENTS AFFECTING THE INDUSTRY

Since 2000, a period of intense change has occurred in the phosphate industry. Traditional European centres of manufacture such as those in Greece, Italy and Spain are progressively closing their plants, with a consequential shift of emphasis in regulatory attention from production operations to the management of legacy issues [26–28]. Countries with emerging economies such as Brazil, China and India have markedly increased their demand for fertilizers in general, and phosphates in particular, for food production [29]. Brazil is importing increased amounts of phosphate fertilizer because its production capacity, although growing, is not keeping pace with domestic demand. China, by contrast, has changed from being a net importer to a net exporter as major new capacity has come on stream [20]. India is almost completely reliant on imported phosphates, but does have some low grade phosphate deposits that may be exploited in the future because of their uranium content [30]. New plants are being planned or built in various parts of the world:

(a) In Saudi Arabia, a major new facility at Ma'aden will, in future, become one of the world's single largest production sites.
(b) In Morocco, additional capacity and new joint ventures are being established at Jorf Lasfar, which is set to remain the world's single largest production site for phosphoric acid.
(c) New facilities and extensions to existing capacity are being constructed in many countries, including Algeria, Brazil, China, Egypt, Jordan, Lebanon and the Syrian Arab Republic.
(d) Malawi intends to establish its own phosphoric acid production capability and many other countries are considering entering the market [29].

Such changes have shifted the centre of gravity of the industry away from countries with developed economies, resulting in decreased production levels and fewer facilities in those countries. The shift is towards countries with emerging and developing economies, where expansion of production capacity is more than offsetting the decrease in production elsewhere. At the same time, some major phosphate rock producing countries such as Morocco are now committed to the introduction of 'value added' activities such as chemical processing and

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granulation, leading to a change in their trading patterns from the mining and shipping of phosphate rock to the production and sale of end products in the form of fertilizer and animal feed. The changes have also brought new challenges for those tasked with maintaining safety standards and best practices in the phosphate industry at both national and international levels [31, 32]. For instance:

(a) The transport and use of phosphate products across geographical and regulatory boundaries are increasing.
(b) Phosphoric acid plants that have ceased production have to be decommissioned.
(c) Neglected or abandoned phosphogypsum stacks have to be reincorporated into a formal management process, which may include finding suitable uses for the material to minimize the amount that has to remain in storage on-site.

Three major new factors in world fertilizer markets as a whole are the projected 70% increase in demand for food by 2050 to feed the growing population, the emergence of a demand for biofuels derived from corn and sugar cane and the surge in demand for animal protein. The demands are growing rapidly, with as yet unknown consequences for patterns of fertilizer consumption. In the USA, a political emphasis on renewable sources of energy, notably biofuels, is having a significant impact on the situation.

In addition, wider sustainability objectives such as those associated with greenhouse gas emissions and the conservation of scarce or non-renewable resources are creating a framework within which the historical role of phosphogypsum as a co-product of phosphoric acid production, rather than as a waste, is being reinvigorated. From the outset, phosphogypsum has been an item of commerce in many countries, with a well-established market value in a variety of applications, especially those in agriculture and construction that have the capacity to consume large volumes [33]. In some markets, however, the commercial use of phosphogypsum has been restricted because of concerns about its radioactivity content and, to a lesser extent, its heavy metals content, even though such concerns appear to be without scientific foundation. In the light of the recent global developments described here, the reasons for treating phosphogypsum as a co-product rather than as a waste become more compelling than ever.

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3. GENERAL RADIATION PROTECTION CONSIDERATIONS

3.1. APPLICATION OF THE STANDARDS TO INDUSTRIAL ACTIVITIES INVOLVING EXPOSURE TO NATURAL SOURCES

3.1.1. Scope of regulation

Paragraph 3.4 of the BSS [2] states that exposure to natural sources is generally considered as an existing exposure situation, meaning that the exposure does not fall within the scope of regulation in terms of the requirements for planned exposure situations. However, some industrial activities giving rise to exposure to natural sources have the characteristics of practices and para. 3.4 of the BSS makes provision for the requirements for planned exposure situations to apply in such cases, depending principally on the activity concentrations of radionuclides of natural origin in the material giving rise to the exposure (in this case, any of the process materials involved). The requirements for planned exposure situations apply if the activity concentration of any radionuclide in the uranium or thorium decay chains is greater than 1 Bq/g or the activity concentration of ^{40}K is greater than 10 Bq/g. As a result of this criterion, the phosphate industry is identified in Ref. [7] as being among those industrial activities that are likely to be subject to the requirements for planned exposure situations.[6]

It is important to note that the use of commodities containing radionuclides of natural origin, such as fertilizer, soil amendments and construction materials, is always subject to the requirements for existing exposure situations, regardless of the activity concentrations.

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[6] These criteria do not apply to radon, existing residues in the environment and commodities such as foodstuffs, drinking water, agricultural fertilizer and soil amendments and construction materials, which are normally treated as existing exposure situations regardless of the activity concentrations of the radionuclides concerned, nor do they apply to material in transport, the criteria for which are specified separately in the Standards (see Section 3.1.3). Exposure of workers to radon is regulated according to the requirements for planned exposure situations if the radon concentration in the workplace remains above the applicable reference level after the implementation of remedial action.

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3.1.2. Graded approach to regulation

Where the activity concentration values specified in Section 3.1.1 are exceeded, a graded approach to regulation as a practice is adopted in accordance with the requirements of the BSS (para. 3.6). The application of the graded approach to the regulation of operations involving exposure to NORM is described in Refs [4, 7] and is summarized in Sections 3.1.2.1–3.1.2.3.

3.1.2.1. Initial assessment

An initial assessment is made of the process, the materials involved and the associated exposures. For industries engaged in the processing of NORM, the exposure pathways to workers and to members of the public that are most likely to require consideration are those involving external exposure to gamma radiation emitted from process material and internal exposure via the inhalation of radionuclides in dust[7]. Consideration of internal exposure via the inhalation of ^{222}Rn and/or ^{220}Rn emitted from process material (leading to exposure to the short lived progeny of these radionuclides) may also be necessary during the exploitation of certain minerals. Internal exposure via ingestion may need to be considered for members of the public (mainly as a result of water pathways) but is unlikely to be of concern for workers under normal operational circumstances.

The assessment of the effective dose received by an individual involves summing the personal dose equivalent from external exposure to gamma radiation over a specified period and the committed equivalent dose or committed effective dose, as appropriate, from intakes of radionuclides over the same period. The assessment method is described in more detail in Ref. [4].

3.1.2.2. Regulatory options

The four basic options open to the regulatory body, in ascending order of degree of control, are as follows:

The regulatory body may decide that the optimum regulatory option is not to apply regulatory requirements to the legal person responsible for the practice. The mechanism for giving effect to such a decision could take the form of an exemption. For exposure to NORM, the exemption criterion given in the BSS [2] is a dose of the order of 1 mSv per year. The background to this criterion is given in Ref. [34], which concludes that exemption is likely to be the optimum option if the material does not give rise to an annual effective dose received by a worker

[7] Dust includes aerosols containing solid and/or liquid particles suspended in air.

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exceeding about 1–2 mSv (this being a small fraction of the occupational dose limit), bearing in mind that the dose received by a member of the public in such circumstances is likely to be lower by at least an order of magnitude [7].

Where the regulatory body has determined that exemption is not the optimum option, the minimum requirement is for the legal person to submit a formal notification to the regulatory body of the intention to carry out the practice. As in the case of a decision to grant an exemption, this is an appropriate option when the maximum annual effective dose is a small fraction of the applicable dose limit, but it provides the added reassurance that the regulatory body remains informed of all such practices and of any changes to such practices that might have significant radiological implications.

Where the level of exposure to NORM is such that neither exemption nor the minimum regulatory requirement of notification is the optimum regulatory option, the regulatory body may decide that the legal person has to meet additional (but limited) obligations to ensure that exposed individuals are adequately protected. These obligations would typically involve measures to keep exposures under review and to ensure that the working conditions are such that exposures remain moderate, with little likelihood of doses approaching or exceeding the dose limit.[8] The mechanism for imposing such obligations on the legal person is the granting of an authorization in the form of a registration [4].

Where an acceptable level of protection can only be ensured through the enforcement of more stringent exposure control measures, an authorization in the form of a licence may be required [4]. This is the highest level of the graded approach to regulation and its use for practices involving exposure to NORM is likely to be limited to operations involving substantial quantities of material with very high radionuclide activity concentrations.

3.1.2.3. Control measures for authorized practices

A detailed account of the control measures that may be appropriate for authorized practices involving work with minerals and raw materials is given in Refs [4, 5]. In terms of the graded approach to regulation, the nature and extent of such measures will be commensurate with the type of practice and the levels of exposure, but will generally entail the establishment of some form of radiation protection programme with suitable provisions for monitoring and dose assessment at a more detailed level than in the initial assessment referred to in Section 3.1.2.1.

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[8] For situations in which workers are exposed to gamma radiation and radionuclides in inhaled dust, Ref. [34] states that "Control, if considered necessary, would include the use of methods to suppress or contain any airborne dusts and general radiological supervision".

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Specific radiological measures in the workplace, such as control of the occupancy period or even shielding, may sometimes be appropriate to minimize external exposure to NORM. Materials with relatively low activity concentrations give rise to modest gamma dose rates (typically no more than a few microsieverts per hour), even on contact. In such cases, discouraging access, for example by storing materials in mostly unoccupied areas, may be sufficient. In areas containing materials with relatively high activity concentrations, physical barriers and warning signs may be necessary.

Exposure to airborne dust is likely to be controlled already in many workplaces through general occupational health and safety (OHS) regulations. Control of air quality for the purpose of minimizing dust levels may also help to reduce radon and thoron concentrations. Therefore, the extent to which existing OHS control measures are effective in minimizing workers' radiation exposure is something that the regulatory body would first need to establish before deciding to impose additional control measures for purely radiological reasons. In some workplaces, existing OHS control measures alone may provide sufficient protection against internal exposure. In other workplaces, additional control measures specifically for radiation protection purposes may become necessary for achieving compliance with the Standards. Engineered controls are the favoured option, with working procedures and, finally, protective respiratory equipment being considered only where further engineering controls are not effective or practicable.

Complete containment of material is often impractical, especially where large quantities of low activity concentration materials are involved and spills and the spread of materials outside the area are often of no radiological significance unless substantial and persistent airborne dust levels result. Prevention of resuspension of dust is, therefore, likely to be the most effective approach. Specific measures to control surface contamination only become meaningful where materials with higher activity concentrations are present.

Worker awareness and training are particularly important for supporting the introduction of local rules and for creating an understanding of the precautions embodied in such rules. The work practices of individual employees may exacerbate dust generation and, in some cases, may completely negate the effect of any engineering controls installed. There may be deficiencies in the way in which equipment maintenance tasks are undertaken, implying the need for periodic review to determine if improvements are possible. The general standard of 'housekeeping' and spillage control also needs to be kept under regular review. Even where the materials being handled have a low activity concentration, a reasonable standard of housekeeping may be necessary to ensure that dust resuspension is adequately controlled.

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3.1.3. Material in transport

3.1.3.1. Basic criteria

The safety requirements for material in transport are set out in the Regulations for the Safe Transport of Radioactive Material (the Transport Regulations) [3]. The transport of material in its natural or processed state, associated with the phosphate industry, may or may not fall within the scope of the Transport Regulations, depending on the activity concentration of the material.

The Transport Regulations only apply if the activity concentration of the material exceeds 10 times the activity concentration for exempt material.[9] For individual radionuclides of natural origin, the activity concentrations for exempt material are shown in Table 3.

3.1.3.2. Mixtures of radionuclides

For mixtures of radionuclides, the activity concentration for exempt material is:

$$X_{\mathrm{m}} = \frac{1}{\sum_i \frac{f(i)}{X(i)}} \qquad (1)$$

where

X_{m} is the activity concentration for exempt material (in Bq/g);
$f(i)$ is the fraction of activity concentration of radionuclide i in the mixture;
$X(i)$ is the activity concentration for exempt material for radionuclide i (in Bq/g);

and the condition for application of the Transport Regulations (see Section 3.1.3.1) is:

[9] This activity concentration criterion applies only to material containing radionuclides of natural origin that is either in its natural state or has been processed only for purposes other than for the extraction of the radionuclides, and that is not intended to be processed for the use of these radionuclides.

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TABLE 3. ACTIVITY CONCENTRATIONS FOR EXEMPT MATERIAL IN TRANSPORT

Nuclide	Activity concentration (Bq/g)	Progeny included in secular equilibrium
U-238 decay series		
U_{nat} (U-238)	1	Th-234, Pa-234m, U-234, Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210
U-238	10	Th-234, Pa-234m
Th-234	1000	Pa-234m
U-234	10, 100[a]	None
Th-230	1	None
Ra-226	10	Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210
Pb-210	10	Bi-210, Po-210
Po-210	10	None
Th-232 decay series		
Th_{nat} (Th-232)	1	Ra-228, Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208 (0.36), Po-212 (0.64)
Th-232	10	None
Ra-228	10	Ac-228
Th-228	1	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208 (0.36), Po-212 (0.64)
Ra-224	10	Rn-220, Po-216, Pb-212, Bi-212, Tl-208 (0.36), Po-212 (0.64)
K-40	100	None

[a] The applicable value depends on the chemical form of the material.

$$\sum_i x(i) > 10X_m \tag{2}$$

where $x(i)$ is the activity concentration of radionuclide i in the mixture.

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Combining Eqs (1) and (2) and making the substitution:

$$f(i) = \frac{x(i)}{\sum_i x(i)} \tag{3}$$

gives the condition for application of the Transport Regulations as:

$$\sum_i \frac{x(i)}{X(i)} > 10 \tag{4}$$

3.1.3.3. Material with decay chains in equilibrium

For material in which the radionuclides in each decay series are (or are deemed to be) in equilibrium, the values of activity concentration for exempt material for U_{nat}, Th_{nat} and ^{40}K (see Table 3) can be used to derive the condition for application of the Transport Regulations, with the progeny of ^{238}U and ^{232}Th automatically being taken into account. Equation (4) then becomes:

$$\frac{x(U_{nat})}{1} + \frac{x(Th_{nat})}{1} + \frac{x(^{40}K)}{100} > 10 \tag{5}$$

For materials that are not particularly rich in potassium, Eq. (5) can be approximated to:

$$x(U_{nat}) + x(Th_{nat}) > 10 \tag{6}$$

3.1.3.4. Material with decay chain segments in equilibrium

The available data on the radionuclide composition of the material may indicate that equilibrium conditions do not prevail throughout the decay chains but that it may be possible to treat the material as a mixture of decay chain segments, each of which can be assumed to be in equilibrium. In such cases, however, the available data and/or the information in Table 3 may not always be sufficiently detailed to determine unequivocally whether the Transport Regulations apply, in which case a conservative estimate may have to be made by assigning the highest individual radionuclide activity concentration in each decay chain or chain segment to all radionuclides in that decay chain or chain segment. Further information on how to proceed when insufficient data are available on

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individual radionuclide activity concentrations is given in the Transport Regulations.

3.2. EXPOSURE TO GAMMA RADIATION

The main radionuclides contributing to gamma exposure are ^{214}Pb and ^{214}Bi from the ^{238}U decay series and ^{228}Ac, ^{212}Pb and ^{208}Tl from the ^{232}Th decay series. The highest gamma energy (2614 keV) is associated with ^{208}Tl. In the phosphate industry, exposure to gamma radiation from radionuclides in the ^{238}U decay series is the main concern for radiation protection and, as in many other NORM industries, arises mainly from accumulations of mineral concentrates or residues. Dose rates are generally highest near process tanks, piping, filters and large material stockpiles. For workers, workplace monitoring or individual monitoring techniques, or a combination of both, are used.

3.3. EXPOSURE TO RADIONUCLIDES IN INHALED DUST PARTICLES

Airborne dust particles arise from the resuspension of dust that has settled on floors and other surfaces, releases from processing operations and the conveying of minerals. For inhalation of such particles by workers in the phosphate industry, exposure to various radionuclides in the ^{238}U decay series (see Appendix I) and to ^{227}Ac in the ^{235}U decay series is the main concern for radiation protection. In situations where the radionuclide activity concentrations in the materials being handled are moderate, it is important to recognize that the silica content of the airborne dust is likely to be of greater concern for occupational health than the radionuclide content.

3.3.1. Particle size

In the absence of particle size information specific to the workplace concerned, an activity median aerodynamic diameter (AMAD) of 5 μm is normally recommended for airborne dust in the workplace [35] and this could be an appropriate value to use in any initial assessment (see Section 3.1.2.1). However, when subsequently performing a more detailed assessment (see Section 3.1.2.3), measurements may indicate that in some workplaces a higher AMAD (e.g. 10 μm) may be more appropriate.

Where high temperature processes are involved, some radionuclides, notably ^{210}Pb and ^{210}Po, can become volatilized in the furnace fume. In the absence of particle size information, an AMAD of 1 μm is normally

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recommended in situations where this fume contaminates the air in the workplace (in the area around the furnace, for instance). In high temperature processes in the phosphate industry, however, a higher AMAD may be appropriate and the best approach is to determine the particle size distribution for the particular workplace concerned.

3.3.2. Monitoring techniques for workers

In the phosphate industry, as with other NORM industries, routine determination of intakes of radionuclides by workers is, in most cases, achieved using techniques based on air sampling. This approach is consistent with the findings of an investigation into monitoring strategies and methods for optimization of internal exposures of workers exposed to NORM carried out for the European Commission [36]. One of the conclusions of that investigation was that "Air sampling, rather than biological sampling (or whole body counting) is the best way of assessing doses and providing ALARA information".

Guidance on the use of techniques based on air sampling for the monitoring of workers is given in Ref. [4]. Such techniques involve the drawing of air through a filter to capture the dust particles, which are then analysed by measuring the activities of alpha emitting radionuclides in the uranium and thorium decay series. The use of these gross alpha activity measurements to determine the intake is subject to the following considerations:

(a) In materials that have not been chemically processed, the equilibrium of the uranium and thorium decay chains is unlikely to be significantly disturbed, allowing equilibrium to be generally assumed for freshly generated airborne dust particles. However, as discussed in the Annex to Ref. [4], some radon and thoron may have escaped from the dust particles when they are analysed in the laboratory after a delay of some days. The resulting depletion in radon and thoron leads to a corresponding depletion in short lived radon or thoron progeny. For minerals likely to be encountered in the phosphate industry, the retention of radon and thoron can be expected to be in the range 50–100% and it would seem reasonable to assume 75% retention as being typical. On this basis, 1 Bq of ^{238}U captured on the filter corresponds to 7.54 Bq of measured gross alpha activity, while 1 Bq of ^{232}Th corresponds to 5.25 Bq of measured gross alpha activity.

(b) In materials that have been subject to chemical processing, equilibrium conditions in the airborne dust particles can no longer be assumed and the analysis may have to include the measurement of certain individual decay progeny.

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Two basic types of air sampling technique are in use: stationary air sampling (also known as workplace or static air sampling), in which the sampling device remains at a fixed location in the workplace, and personal air sampling, in which the sampling device is attached to the worker in a position such that the air sample is reasonably representative of the air breathed by the worker. The use of stationary air sampling is generally less preferred for dose assessment purposes because the air that is sampled may not be representative of the air breathed by the worker. It is noted in Ref. [36] that the use of stationary air sampling can result in dust inhalation doses being significantly underestimated, sometimes by several orders of magnitude, particularly in workplaces where the resuspension of dust by worker activities is a significant factor. On the other hand, stationary air sampling may result in a significant overestimation of the dose if the worker is not continuously stationed in a dusty area. Three different airborne dust sampling conventions have been established, reflecting different size fractions of the airborne dust particles:

(i) The inhalable fraction (involving AMADs of up to about 100 μm) includes all airborne particles entering the body through the nose and/or mouth during breathing;
(ii) The thoracic fraction (involving AMADs of up to about 30 μm) is the sub-fraction of the inhalable fraction that can penetrate into the tracheo-alveolar region of the lung;
(iii) The respirable fraction (involving AMADs of up to about 10 μm) is the sub-fraction of the inhalable fraction that penetrates into the alveolar region of the lung, including the respiratory bronchioles, the alveolar ducts and sacs.

The selection of the most suitable air sampling device should be based on which dust fraction is to be sampled. A device incorporating an IOM[10] cassette for sampling the inhalable fraction is shown in Fig. 3. The cassette has a 50% sampling efficiency at an AMAD of 40 μm. A sampling device for the thoracic fraction is shown in Fig. 4.

Owing to difficulties in applying personal air sampling to every exposed worker all of the time, monitoring strategies usually involve the assignment of workers to work categories that reflect the general nature and scope of the work activities. In many workplace situations involving exposure to dust containing radionuclides of natural origin, such exposure is not uniform within a work category since a worker may spend time in different exposure environments during the course of the work shift. A further complication arises in accounting for the wearing of respiratory protective equipment.

[10] IOM: Institute of Occupational Medicine, Edinburgh, UK.

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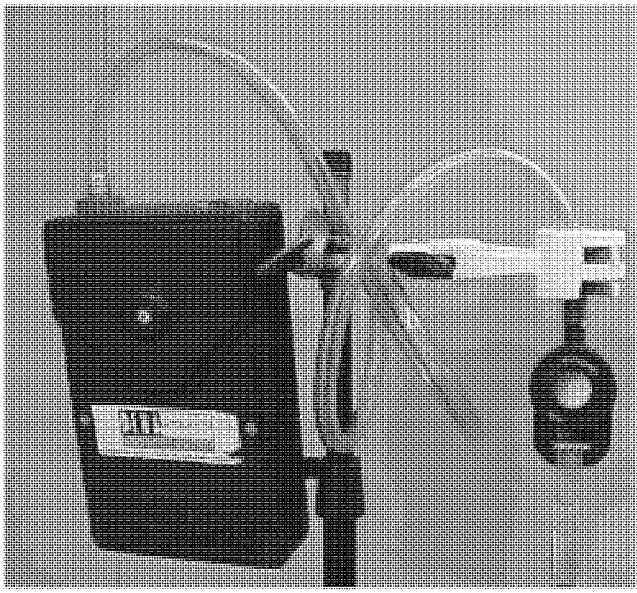

FIG. 3. Personal air sampling device for the inhalable dust fraction (courtesy: Thermphos International, Netherlands).

FIG. 4. Personal air sampling device for the thoracic dust fraction (courtesy: Thermphos International, Netherlands).

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Air sampling equipment and techniques have been reviewed in terms of their applicability to radiation protection in workplaces involving exposure to radionuclides in airborne dust [36]. Some of the findings of that review are summarized in the following:

(a) Since air samplers are designed to follow a specific particle size sampling convention based on industrial hygiene sampling criteria, they typically underestimate the true ambient aerosol and thus the activity inhaled. The degree of underestimation depends on the AMAD and geometric standard deviation (GSD) of the particle size distribution of the ambient aerosol and on the type of sampler used. A correction factor can be applied to minimize the degree of underestimation of the airborne activity concentration but this does not remove all of the uncertainty because the AMAD and GSD vary with location, time and circumstances of dust production and can, therefore, never be known precisely.

(b) The aerosol particle size distribution also has a significant effect on the dose coefficient (the committed effective dose per unit intake of activity), leading to an additional source of uncertainty when assessing the effective dose due to the inhalation of particles. The dependence of the dose coefficient on AMAD is particularly strong for particles of lung absorption class S. When assessing the effective dose, it is important to select a sampler with an efficiency that follows as closely as possible the AMAD dependency of the relevant dose coefficients.

(c) Knowledge of the lung absorption class is important because it is needed for determining not only the most appropriate dose coefficient but also the type of sampler that best minimizes the errors arising from an incomplete knowledge of the particle size distribution.

(d) The preferred type of sampling for minimizing dose assessment errors is inhalable sampling for particles in lung absorption class F and thoracic sampling for particles in lung absorption classes M and S. While particles of class M or S are likely to be encountered in many NORM industries, it is pointed out that thoracic samplers are presently not as widely available as inhalable samplers and often are not suitable for alpha counting owing to the dust particles being collected on foam rather than flat filters.

(e) Where the particle size distribution is not known, the assignment of an AMAD of 5 μm has been found reasonable in minimizing errors in assessing the effective dose, whatever the true value of AMAD, sampling

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type, radionuclide and lung absorption class.[11] The assignment of a GSD of 2.5 is recommended by the International Commission on Radiological Protection (ICRP) for aerosols with an AMAD greater than 1 μm when the actual value is unknown [37]. For a GSD of 2.5, sampling efficiency correction factors, as referred to in (a), are given in Table 4.

The activity inhaled by workers, as determined from the alpha counting of dust samples collected on filters, may be underestimated if there is significant alpha particle self-absorption in large particles or in multilayers or agglomerates of smaller particles deposited on the filter. In such cases, dust loadings on filters may need to be restricted accordingly [38]. Various types of filter medium and sampling cassette are available. Where the dust concentration is relatively low (say, about 1–2 mg/m^3) and sampling is undertaken over a 4–6 h period, the choice of filter medium and cassette is not likely to be critical. However, when the dust concentration is relatively high (more than about 3 mg/m^3) and the sampling is undertaken over a period of 8 h or more, the selection of equipment requires more careful consideration. For some types of filter medium, such as PVC, part of the sample may be lost as a result of dust not fully adhering to the surface of the filter. For some types of monitoring cassette, the dust may adhere to the inside wall, requiring it to be removed by washing and added to the material collected on the filter prior to radiometric analysis.

3.3.3. Calculation of effective dose

Dose coefficients (values of committed effective dose per unit intake of activity) for inhalation of radionuclides by workers and members of the public are

TABLE 4. SAMPLING EFFICIENCY CORRECTION FACTORS FOR ESTIMATING THE AIRBORNE ACTIVITY CONCENTRATION OF PARTICLES WITH A GSD OF 2.5 [36]

AMAD (μm)	Correction factor		
	Inhalable sampler	Thoracic sampler	Respirable sampler
1	1.04	1.05	1.11
5	1.18	1.41	2.5
10	1.31	2.1	5.6

[11] The measurement of the AMAD requires specialized equipment such as a cascade impactor.

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specified in a database compiled by the ICRP [39]. The values are based on the model for the respiratory tract described in Ref. [37]. The dose coefficients for workers quoted in Ref. [39] cover a wide range of AMADs. Most of the values for AMADs of 1 and 5 μm appear also in Table III-2A in Schedule III of the BSS [2]. The dose coefficients for members of the public are specified in Ref. [39] for a default AMAD of 1 μm and also in Table III-2E in Schedule III of the BSS [2].

It is pointed out in Ref. [36] that in most NORM industries, the radioactive components of the material involved, and thus of its aerosol particles, are contained within a matrix of non-radioactive elements and their compounds. These matrices often determine the solubility of the particles and it is, therefore, appropriate in such cases to choose the same lung absorption class for all the radionuclides contained within them. It is further pointed out that many of these materials are resistant to all but the most vigorous forms of chemical attack and that their dust particles are obviously lung absorption class S. This reportedly applies to radium rich process scales of the type likely to be encountered in the phosphate industry. However, lung absorption class S may not be appropriate for materials that have been subjected to vigorous chemical treatment. In such cases, it may be more appropriate to determine the lung absorption class experimentally for the particular material involved.

In high temperature processes, the volatile radionuclides ^{210}Pb and ^{210}Po are likely to be removed from the original mineral matrix. When assessing doses arising from the inhalation of furnace fume and precipitator dust, therefore, the most appropriate lung absorption class needs to be determined experimentally.

Inhalation dose coefficients applicable to workers in industrial operations involving low solubility airborne dust particles are given in Table 5. The coefficients relate to lung absorption class S to the extent possible and cover all radionuclides with significant dose contributions. In the few instances where a value for class S is not available, the value given is that corresponding to the next fastest lung absorption class for which information is available.[12] Most of the values in Table 5 are taken from Ref. [39]. In some cases (denoted by bold figures), values for lung absorption class S are not available from this source and data are quoted instead from the results of other calculations [36, 40] based similarly on the ICRP respiratory tract model described in Ref. [37]. Table 6 sets out the inhalation dose coefficients applicable to workers in industrial operations involving medium solubility airborne dust particles such as those that might occur in chemical processing facilities. The coefficients relate to lung absorption class M and are taken from Ref. [39] or, for those figures in bold, from Ref. [36].

[12] The use of dose coefficients for lung absorption classes other than class S in these few instances may lead to some underestimation of the dose.

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TABLE 5. RADIONUCLIDE SPECIFIC INHALATION DOSE COEFFICIENTS FOR WORKERS (LOW SOLUBILITY DUST PARTICLES)

Radionuclide	Dose coefficient for specified AMAD (μSv/Bq)[a]				
	0.3 μm	1 μm	3 μm	5 μm	10 μm
Uranium decay series					
U-238	10	7.3	7.2	5.7	3.5
U-234	12	8.5	8.6	6.8	4.1
Th-230	18	13	10	7.2	5.2
Ra-226	4.4 (M)	**8.7**	**8.7**	**6.9**	**4.2**
Pb-210	0.76 (F)	**5.2**	**5.3**	**4.3**	**2.7**
Po-210	3.9 (M)	**3.9**	**3.5**	**2.7**	**1.7**
Ac-227 (from U-235 series)[b]	88	66	52	47	27
Series in equilibrium[b,c]	53.1	49.6	45.7	35.8	22.6
Thorium decay series					
Th-232	32	23	17	12	8.1
Ra-228	3.3 (M)	**15**	**14**	**11**	**7.1**
Th-228	45	37	33	25	18
Ra-224	3.3 (M)	2.9 (M)	3.1 (M)	**2.8**	1.3 (M)
Series in equilibrium[c]	83.6	77.9	67.1	50.8	34.5

[a] The dose coefficients quoted are those corresponding to lung absorption class S, except where specified in parentheses as M or F. Values shown in bold are taken from Ref. [36] (rounded to two significant figures) or, in the case of ^{224}Ra, from Ref. [40]. All other values are taken from Ref. [39].

[b] The natural abundance of U-235 is 0.711%, resulting in an activity concentration in natural uranium of 0.046 relative to that of U-238. Consequently, the relative contributions to the inhalation dose from the U-235 decay series radionuclides are insignificant except for that from Ac-227. The dose coefficient for Ac-227 is multiplied by 0.046 in calculating the dose coefficient for the full series.

[c] The values refer to the dose per unit activity of the parent radionuclide.

Many assessments of worker doses reported for NORM industries are based on the inhalation dose coefficients given in Table III-2A in Schedule III of the BSS [2] for AMADs of 1 or 5 μm, since these coefficients, by international consensus, provide the basis for regulation in accordance with the Standards. However, the BSS do not provide coefficients for ^{228}Ra, ^{224}Ra, ^{226}Ra, ^{210}Pb and ^{210}Po in lung absorption class S, with the result that, for low solubility particles, the coefficients for class M (or F in the case of ^{210}Pb) have to be used instead. For medium solubility particles, the coefficients for lung absorption class F have to be

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TABLE 6. RADIONUCLIDE SPECIFIC INHALATION DOSE COEFFICIENTS FOR WORKERS (MEDIUM SOLUBILITY DUST PARTICLES)

Radionuclide	Dose coefficient for specified AMAD (μSv/Bq)[a]				
	0.3 μm	1 μm	3 μm	5 μm	10 μm
Uranium decay series					
U-238	3.8	2.6	2.2	1.6	1.1
U-234	4.4	3.1	2.7	2.1	1.4
Th-230	51	40	35	28	17
Ra-226	4.4	3.2	2.8	2.2	1.5
Pb-210	0.76 (F)	**1.0**	**0.93**	**0.74**	**0.45**
Po-210	3.9	3.0	2.8	2.2	1.1
Ac-227 (from U-235 series)[b]	260	210	180	150	90
Series in equilibrium[b,c]	80.2	62.6	54.7	43.7	26.7
Thorium decay series					
Th-232	54	42	37	29	18
Ra-228	3.3	2.6	2.2	1.7	0.98
Th-228	36	30	28	22	12
Ra-224	3.3	2.9	3.1	2.4	1.3
Series in equilibrium[c]	96.6	77.5	70.3	55.1	32.3

[a] The dose coefficients quoted are those corresponding to lung absorption class M, except where specified in parentheses as F. Values shown in bold are taken from Ref. [36] (rounded to two significant figures). All other values are taken from Ref. [39].

[b] The natural abundance of U-235 is 0.711%, resulting in an activity concentration in natural uranium of 0.046 relative to that of U-238. Consequently, the relative contributions to the inhalation dose from the U-235 decay series radionuclides are insignificant except for that from Ac-227. The dose coefficient for Ac-227 is multiplied by 0.046 in calculating the dose coefficient for the full series.

[c] The values refer to the dose per unit activity of the parent radionuclide.

used for ^{210}Pb. In addition, the dose coefficients for ^{228}Th given in the BSS are different from those incorporated into the ICRP database [39] and given in Tables 5 and 6. For airborne dust particles likely to be encountered in the phosphate industry, the implications of using the BSS coefficients instead of those in Tables 5 and 6 can be estimated from the expected radionuclide solubilities and concentrations in the various process materials. It is found that the implications are significant only for radionuclides of low solubility and depend mainly on the relative concentrations of ^{226}Ra and its progeny. In summary:

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(a) For particles of phosphate ore, phosphate rock or phosphogypsum, all radionuclides can be assumed to be of low solubility. For phosphate ore and phosphate rock, in which near equilibrium conditions prevail, the use of BSS dose coefficients could lead to an underestimation of the inhalation dose by up to 20%. For phosphogypsum, in which there is a high degree of disequilibrium with a characteristically high ^{226}Ra content, the use of BSS coefficients could lead to a more serious underestimation of up to 40%.

(b) For particles of fertilizer product, the decay chains are not in equilibrium and the radionuclide solubility could be regarded as either low or medium, depending on the radionuclide (see Section 6.3.2). Since the concentrations of ^{226}Ra and its progeny are characteristically low, the use of BSS dose coefficients will give doses very similar to those calculated using the coefficients in Tables 5 and 6.

The derivation of the dose coefficients for ^{226}Ra specified in the ICRP database [39], the BSS [2] and Tables 5 and 6 is based on the assumption that ^{222}Rn produced in the respiratory tract does not have the same biokinetic behaviour as its parent ^{226}Ra, but rather is removed to the environment at a rate of 100 d^{-1} (see Annex B of Ref. [41]). Should the removal rate be lower than 100 d^{-1}, the use of these dose coefficients would, by implication, result in the dose being underestimated. In an extreme (and highly unlikely) situation of zero radon removal from the respiratory tract, calculations based on data reported in Ref. [36] suggest that the degree of underestimation could be about 50% for particles of phosphate ore, phosphate rock and phosphogypsum and about 10% for particles of fertilizer.

3.4. SELECTIVE MIGRATION OF RADIONUCLIDES

The mining and beneficiation of phosphate ore involves only physical processes and is, therefore, unlikely to affect the equilibrium that generally exists in the ore. However, chemical or thermal processing of phosphate rock will mobilize the ^{238}U and ^{232}Th decay series radionuclides contained in the ore. This causes different radionuclides to migrate in different ways, thus destroying the equilibrium condition. A knowledge of the resulting radionuclide compositions of the various process materials and products is essential for determining the nature of any control measures that might be needed to ensure that the workers and members of the public are adequately protected.

As an illustration of radionuclide migration during the processing of phosphate ore into fertilizer, a mass balance and a radionuclide balance for a wet process facility processing sedimentary rock are shown in Fig. 5. The activity

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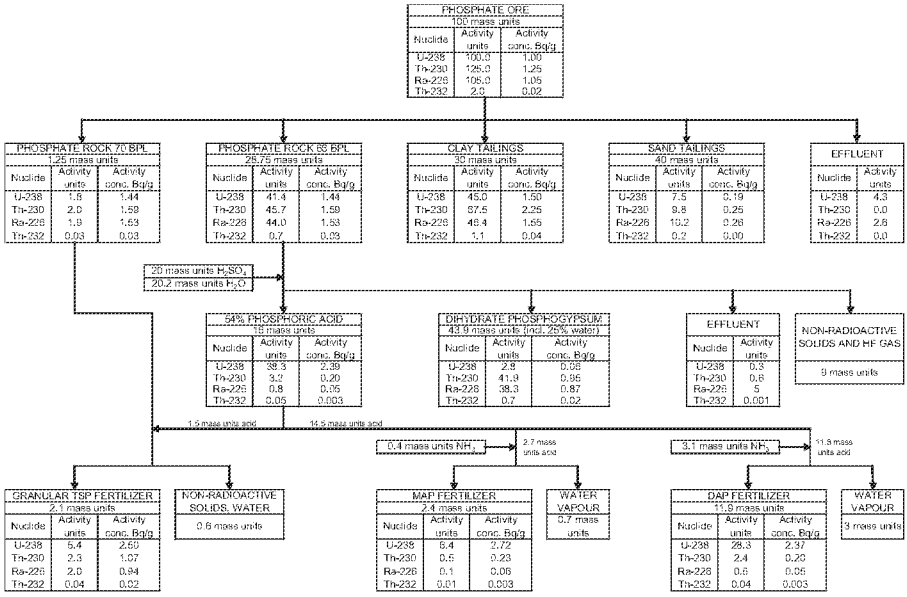

FIG. 5. Typical mass balance and radioactivity balance in the production of phosphate fertilizers in central Florida, USA.

concentrations used in this example are typical of those measured in fertilizer production facilities in central Florida, USA, using local phosphate ore as a feedstock. The relative amounts of the three types of fertilizer shown in Fig. 5 reflect current production patterns. For the production of MAP and DAP fertilizers, phosphate rock with a P_2O_5 content of 30% (66 BPL) is assumed in Fig. 5. This reflects typical historical production values. The exhaustion of high grade rock together with improvements in beneficiation and chemical processing technology has enabled the exploitation of ores with values as low as 24% (52 BPL). During the digestion of the rock with sulphuric acid, the uranium contained within it migrates primarily to the phosphoric acid, whereas most of the radium ends up in the phosphogypsum. The radionuclide composition of the phosphoric acid is, in turn, carried through to the various fertilizer products that are derived directly from it.

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4. MINING AND BENEFICIATION OF PHOSPHATE ORE

4.1. PROCESS DESCRIPTION

4.1.1. Mining

Most commercially exploited sedimentary phosphate deposits are located within a few tens of metres of the earth's surface. These deposits are usually mined by opencast techniques, although some underground mining has been carried out in Egypt, Morocco and the Russian Federation. The overburden and phosphate ore are usually removed by large excavating machines such as electrically operated draglines (see Fig. 6), bucket wheel excavators or electric shovels. In smaller operations, wheeled loaders or hydraulic excavators may be used. Sedimentary phosphate ore currently mined in the USA contains sand, clay, fine particles of phosphate and, in the Florida operations, larger phosphate 'pebbles'. A sample of sedimentary ore from central Florida is shown in Fig. 7. In the mining of igneous deposits and some sedimentary deposits, the overburden and/or phosphate ore has to be broken up by drilling and blasting before it can be removed. The overburden may be set aside for future use in the mine remediation

FIG. 6. Dragline (courtesy: Florida Industrial and Phosphate Research Institute).

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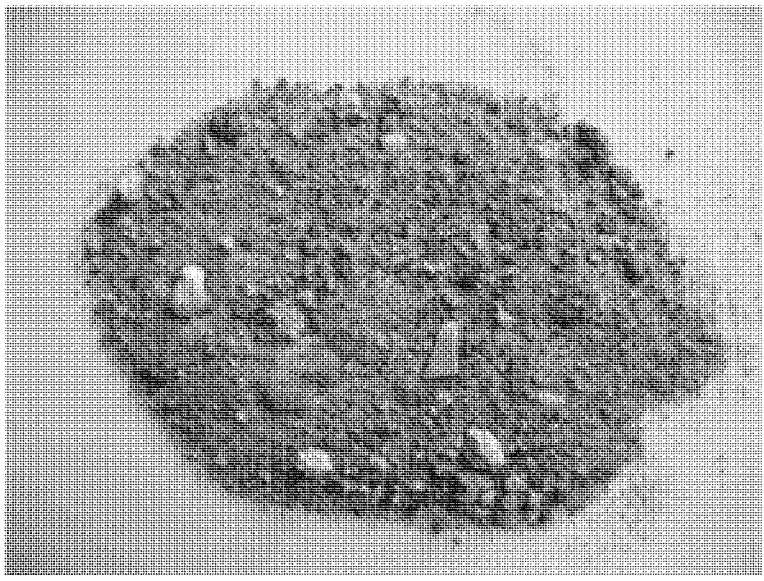

FIG. 7. Phosphate ore of sedimentary origin.

process or returned directly to the mined-out pit area. In some operations the mined ore is exposed to high pressure water jets, as shown in Fig. 8. This generates a slurry, which is pumped directly to the beneficiation plant through a pipeline, as shown in Fig. 9. In other mining operations, the ore may first have to be loaded into trucks for haulage to a nearby crushing facility, after which the crushed ore is transported to the beneficiation plant by a slurry pipeline, train or conveyor. In some hard rock operations, such as those handling ore of igneous origin, the rock is first crushed and then transported by a conveyor to a wet or dry milling facility, after which the milled ore is transported to the beneficiation plant by a slurry pipeline.

4.1.2. Beneficiation

A typical beneficiation process for sedimentary rock is shown schematically in Fig. 10. The first step is usually a wet screening operation ('washing') designed to clean and separate the larger phosphate particles from the slurry and to disintegrate mechanically the large balls of clay. The equipment used may include vibrating and stationary screens as well as log washers, hydrocyclones and clay disintegrators. In operations in Florida, USA, phosphate pebbles (see Fig. 11) are screened out from the clay, sand and sand sized phosphate rock, moved to dewatering tanks and stockpiled by conveyors for

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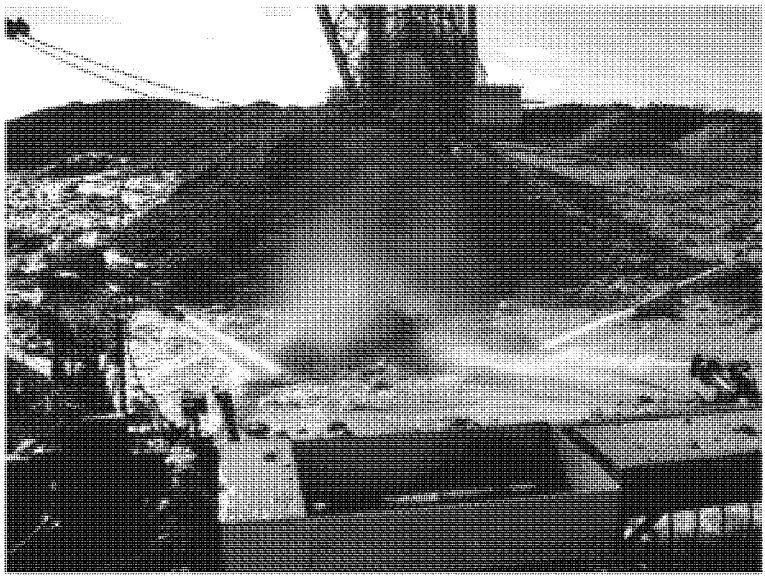

FIG. 8. High pressure water jets (courtesy: Florida Industrial and Phosphate Research Institute).

FIG. 9. Slurry pipeline (courtesy: Florida Industrial and Phosphate Research Institute).

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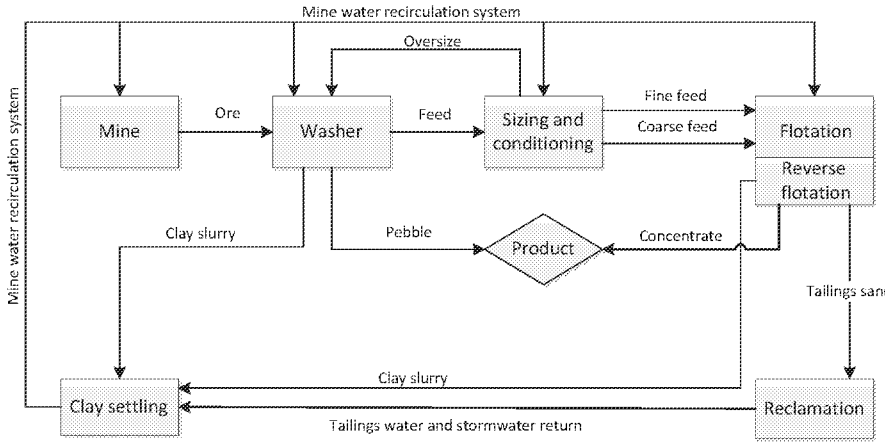

FIG. 10. Basic mining and beneficiation process used in Florida, USA.

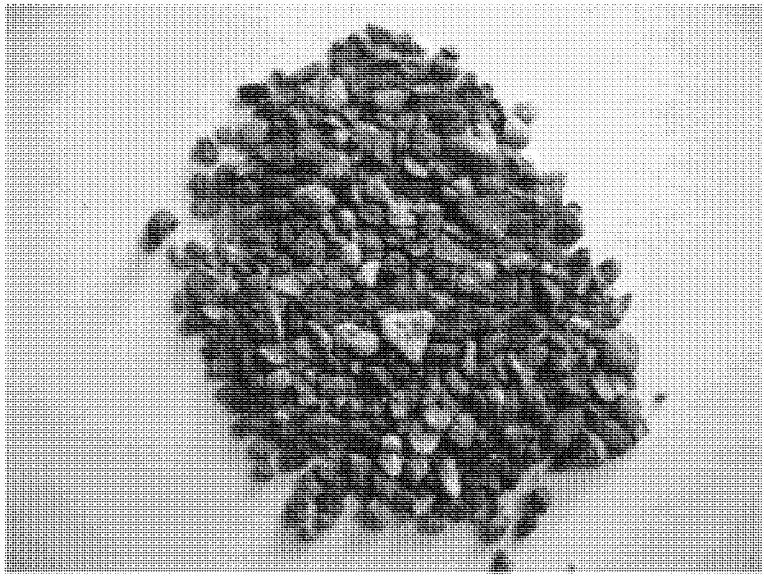

FIG. 11. Phosphate rock (pebble).

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further processing. The clay particles removed from the slurry during the washing process are usually pumped through pipelines to clay storage ponds where the clay slowly settles to the bottom. Clear water is drawn from the top of the pond and pumped back to the beneficiation plant for reuse.

Depending on the characteristics of the ore and the desired quality of the phosphate rock product, ore that has been wet screened may occasionally require no further processing other than dewatering (either naturally or using a centrifuge) and kiln drying. Usually, however, the ore needs to be further upgraded. It is sent to a flotation plant (see Fig. 12) in which various reagents such as fuel oil, soap and fatty acids are used to separate the phosphate particles from residual sand particles. These reagents coat the phosphate particles, allowing increased bonding with the air bubbles released from the bottom of the flotation chamber. The phosphate particles attached to the bubbles are transported to the top of the chamber where they are skimmed off mechanically, as shown in Fig. 13, and scrubbed with dilute sulphuric acid to remove the organic reagents. The material is then frothed with amines to float the remaining quartz. The phosphate rich fraction is pumped to large dewatering vessels, dried and stored in preparation for despatch as 'phosphate rock', the final product of the beneficiation process (see Fig. 14). The sand is pumped back into the mining void

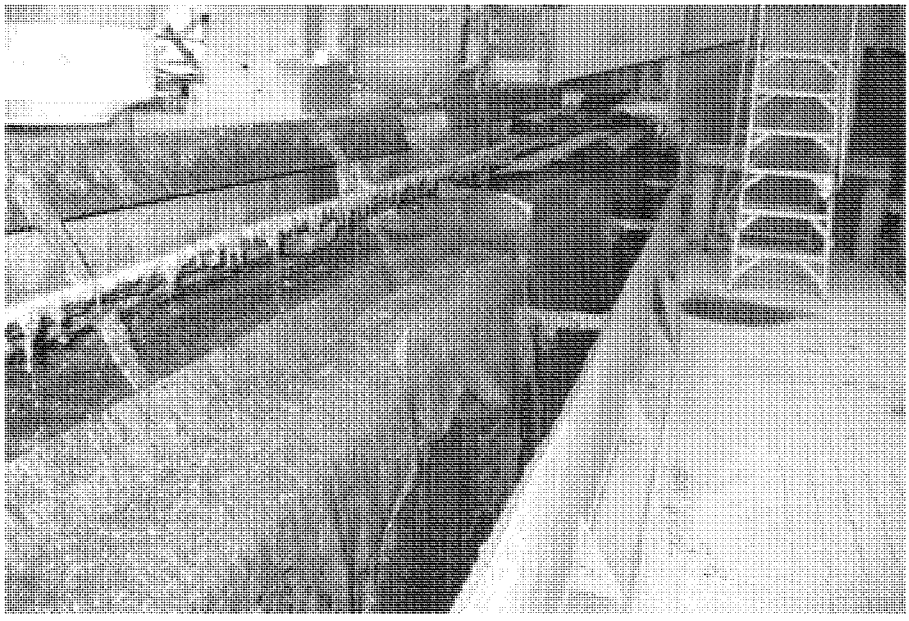

FIG. 12. Flotation plant (courtesy: Florida Industrial and Phosphate Research Institute).

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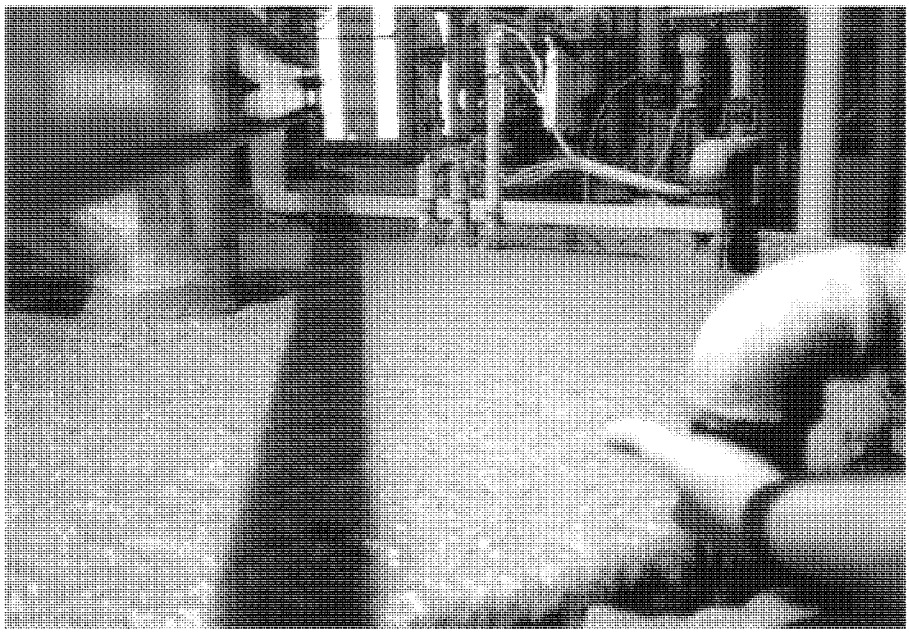

FIG. 13. Flotation column cell (courtesy: Florida Industrial and Phosphate Research Institute).

FIG. 14. Phosphate rock (concentrate).

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(see Fig. 15) or stockpiled for future use, for example in land remediation. An aerial view of a typical beneficiation plant, illustrating the general plant layout, is shown in Fig. 16 and a closer view of the layout of the beneficiation process is shown in Fig. 17.

Depending on the mineralogy of the ore body, additional process steps may be included in the beneficiation process to remove specific impurities. For instance:

(a) Some phosphate ores contain significant amounts of calcium carbonate (in the form of dolomite or calcite) and/or carbonaceous gangue and organic material. For such ores, a calcining step may be included in the beneficiation process.[13] This involves heating the material to 800–950°C to decompose the impurities and facilitate their removal. The calcining process also improves the reactivity of the rock. Calcining is known to be used in India and Morocco and has been proposed for use in future operations in Saudi Arabia.

FIG. 15. Sand tailings pumped back to the mine cut (courtesy: Florida Industrial and Phosphate Research Institute).

[13] Calcining is a process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates or other compounds are decomposed and the volatile material expelled.

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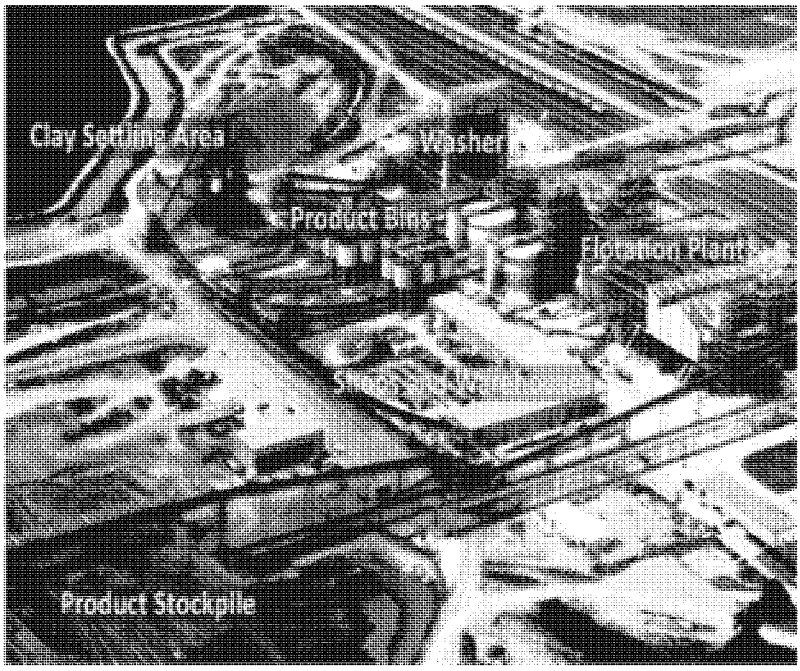

FIG. 16. Overall beneficiation plant layout.

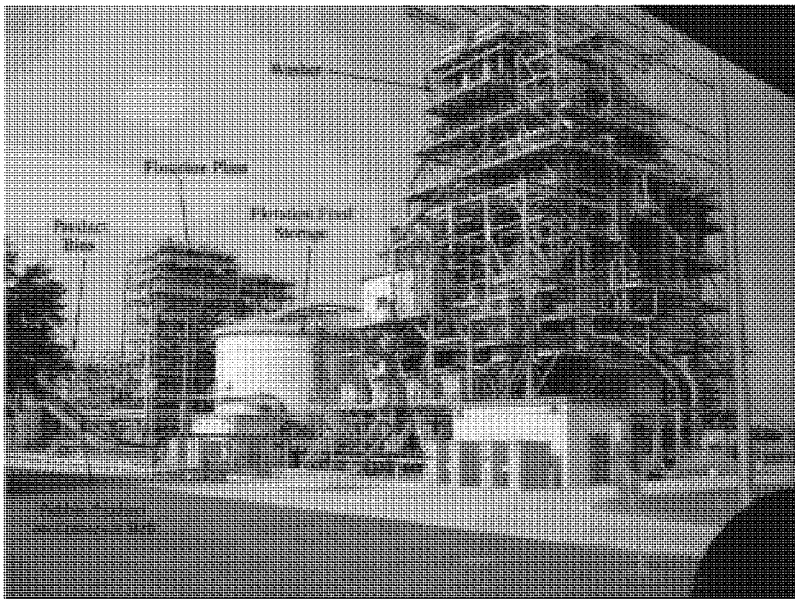

FIG. 17. Layout of the beneficiation process.

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(b) Some igneous ores contain significant amounts of iron, much of which may be removed by magnetic separation techniques. Such techniques are known to be used in Brazil, Canada, Egypt and South Africa.

Specific impurities removed from the ore are sometimes recovered as by-products. In South African igneous phosphate operations, for instance, copper sulphide concentrate and magnetite are recovered for smelting and for use in coal washing, respectively. In some Brazilian operations, baryte and/or magnetite are recovered as by-products.

Data on the chemical composition of phosphate rock are given in Appendix IV. The beneficiation process, by its very nature, gives the phosphate rock a more consistent composition than that of the original ore and, of course, a higher P_2O_5 content. The composition can be summarized as follows:

For phosphate rock of sedimentary origin, the P_2O_5 content is 23–37%. The other major component is CaO, with a concentration of 44–52%. The content of P_2O_5 and CaO combined (tricalcium phosphate) is 80–85%.

Phosphate rock of igneous origin contains higher concentrations of both P_2O_5 (35–42%) and CaO (51–54%). The content of P_2O_5 and CaO combined (tricalcium phosphate) is about 90%.

The fluorine content of phosphate rock (2–4%) is not appreciably different from that found in the ore.

The cadmium content of phosphate rock of sedimentary origin is highly variable within the range 0–100 ppm, whereas the cadmium content of phosphate rock of igneous origin is consistently low (0.25–2 ppm).

Maintenance of the beneficiation plant typically involves the removal of scale and the generation of surface contaminated scrap metal. As there are no chemical changes to the material during the beneficiation process, the selective precipitation of specific elements, including radioactive species, has not been found. Any scales observed consist of hardened phosphate rock or tailings material.

4.1.3. Bulk transport of phosphate rock

In highly industrialized phosphate producing countries such as the USA, it is common for the phosphate rock produced by the beneficiation process to be fed to a chemical processing plant located nearby, often on the same site. The transfer of the phosphate rock to the chemical process plant (or, in some cases, first to a milling facility) is accomplished either in dry form using rail cars, trucks or covered conveyors or as a slurry in a pipeline. When covered conveyors are used, workers using earth moving equipment push the rock from stockpiles into open chutes where the rock falls onto the conveyor.

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In the less industrialized phosphate producing countries, it has been common practice for the phosphate rock to be exported without any further processing. This has necessitated the bulk transport of phosphate rock, often over very large distances, by sea, inland waterway, rail and/or road. However, this situation is changing as a result of increasing transport costs and the tendency for some major rock producing countries to focus more on 'value added' activities such as chemical processing and subsequent conversion into granulated fertilizer (see Section 2.5). As a result, the bulk shipment of rock is beginning to decline in favour of the shipment of fertilizer products.

4.2. RADIONUCLIDE ACTIVITY CONCENTRATIONS

4.2.1. Phosphate ore

Cationic radionuclide substitutions in the apatite structure of phosphate ore may include U^{4+}, U^{6+}, Th^{4+}, Ra^{2+}, Pb^{4+}, Pb^{2+}, Po^{4+} and Bi^{3+}. Substitutions may also occur in other minerals incorporated in phosphate ore or may be adsorbed on the surfaces of such minerals. The proportion of uranium substitutions involving the U^{4+} ion is reported to be 40–91% (mean 65%), with the balance involving the U^{6+} ion [42]. It is assumed that U^{4+} substitutes for Ca^{2+} in the apatite structure because these two ions have almost identical ionic radii. However, this type of substitution is limited because the number of Ca^{2+} ions is more than 25 000 times higher than the number of U^{4+} ions available for substitution and there are other, more plentiful, substitute ions available such as sodium and magnesium. Calcium ions may also be substituted with radium, lead, thorium and polonium ions. Uranium concentrations in phosphate ore are given in Table 7.

Data on radionuclide activity concentrations in phosphate ores are given in Appendix II. The following general conclusions can be drawn from these data:

(a) In currently exploited sedimentary phosphate ores, the concentrations of individual ^{238}U series radionuclides generally range from about 0.5 to 3 Bq/g whereas the concentrations of ^{232}Th series radionuclides are generally not significantly elevated above values found in normal rocks and soils.

(b) In currently exploited igneous phosphate ores, the concentrations of both the ^{238}U and the ^{232}Th series radionuclides are elevated (to about 0.1–0.2 Bq/g and 0.1–0.4 Bq/g, respectively). When compared with sedimentary phosphate deposits, the ^{238}U series radionuclide concentrations are lower but the ^{232}Th series radionuclide concentrations are higher.

(c) In ores of both sedimentary and igneous origin, the ^{238}U and ^{232}Th decay chains are generally in radioactive equilibrium.

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TABLE 7. URANIUM IN PHOSPHATE ORE (BY COUNTRY)

Country	Concentration of uranium as U_3O_8 (%)	Reference
Algeria	0.011–0.014	[12]
Brazil	0.008	[12]
India:		[30]
Mussorie	0.04	
Karnataka	0.03–0.08	
Israel	0.005–0.015	[12]
Jordan	0.012–0.015	[12]
	0.024	[43]
Morocco	0.009–0.014	[12]
	0.023	[44]
Tunisia	0.005–0.01	[12]
USA:		
Florida	0.015–0.018	[45]
North Carolina	0.008	[12]

Overall, the activity concentrations in currently exploited phosphate ores are about 0.1–3 Bq/g for radionuclides in the ^{238}U decay series and 0.1–0.4 Bq/g for radionuclides in the ^{232}Th decay series.

4.2.2. Phosphate rock

Data on the radionuclide activity concentrations in phosphate rock product are given in Appendix IV. In summary:

(a) The ^{238}U concentrations in phosphate rock originating from sedimentary deposits generally fall within the range 0.2–2.5 Bq/g.

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(b) The ^{238}U concentrations are significantly lower in phosphate rock originating from igneous deposits (0.03–0.18 Bq/g).
(c) The ^{232}Th concentrations in products of sedimentary origin, as well as in igneous product from Kola, Russian Federation, generally fall within the range 0.01–0.1 Bq/g.
(d) The ^{232}Th concentrations in the igneous product from South Africa (0.3–0.4 Bq/g) are significantly higher than the levels found in most sedimentary products.
(e) The situation regarding other radionuclides in the ^{238}U and ^{232}Th decay series is similar to that for the original phosphate ore. In most cases, the ^{238}U and ^{232}Th decay chains appear to be in approximate radioactive equilibrium [46, 47].

4.2.3. Tailings

A summary of available information on radionuclide activity concentrations in tailings is given in Table 8. The concentrations are generally similar to those in the ore from which they are derived, although for central Florida operations, this is true only for clay tailings — the radionuclide concentrations in sand tailings are typically an order of magnitude lower.

4.3. OCCUPATIONAL EXPOSURE

4.3.1. Exposure pathways

External exposure to gamma radiation occurs through proximity to bulk quantities of process materials, but the degree of such exposure is limited by several factors. Workers in the mining areas operate heavy equipment such as draglines and pit cars and this equipment provides a significant amount of shielding of the operators from gamma radiation. Workers in beneficiation plants spend only limited periods close to bulk material and are shielded by containers and liquids.

Internal exposure occurs through the inhalation of radionuclides in airborne dust while working in the operational areas of the mine and beneficiation plant. The excavation, conveying, crushing, grinding and other handling of dry phosphate rock can generate significant amounts of airborne dust. In the case of wet mining and beneficiation processes, however, dust inhalation is not a significant exposure pathway, even with the highest activity concentrations in known ore bodies, because dust is suppressed by the water used to break up and transport the ore. Exposure to airborne dust may also occur while handling waste

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TABLE 8. RADIOACTIVITY IN TAILINGS FROM THE BENEFICIATION OF PHOSPHATE ROCK

Source	Activity concentration (Bq/g)[a]				
	U-238	Th-230	Ra-226	Th-232	Th-228
Tailings from sedimentary ore[b]					
USA, central Florida (clay) [16, 47]	0.6–1.8	2.3	0.5–1.9	0.04	—
USA, central Florida (sand) [16, 47]	0.055–0.4	0.25	0.06–0.45	0.004	—
USA, northern Florida [47]	0.01–0.03	—	0.07–0.1	—	—
Tailings from igneous ore					
South Africa [48]	0.26 (0.22–0.30)	—	0.25 (0.19–0.28)	0.33 (0.26–0.44)	0.34 (0.22–0.46)

[a] Some values have been rounded.

[b] Higher values than those listed in the table have been encountered, but these are not representative of current commercial operations. In tailings from former sedimentary phosphate mining in the United Republic of Tanzania, the activity concentrations were 4.3 Bq/g for ^{226}Ra and 0.6 Bq/g for ^{228}Ra and ^{228}Th [49].

materials and surface contaminated objects and while cleaning or refurbishing contaminated equipment.

In opencast mining operations, no significant buildup of radon daughters occurs. Similarly, beneficiation plants are open to outside air exchange and there is again little opportunity for the buildup of radon progeny above ambient levels. If mining is conducted underground, opportunities exist for the significant buildup of radon progeny in the workplace atmosphere, with the extent of any such buildup depending strongly on the ventilation conditions.

4.3.2. Exposure levels

4.3.2.1. Gamma dose rates

For the relatively low concentrations of ^{238}U and ^{232}Th decay series radionuclides in phosphate ore and phosphate rock, the dose rate depends primarily on the activity concentration of the material rather than its total quantity and geometry. Using a theoretical modelling technique described in Ref. [50], gamma dose rates per unit activity concentration have been calculated at a

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distance of 1 m from a 1000 m^3 volume of material in which radionuclides in each of the ^{238}U and ^{232}Th decay series were assumed to be in equilibrium. The predicted dose rate associated with uranium series radionuclides is 0.39 μSv/h per unit activity concentration of ^{238}U (in becquerels per gram). For thorium series radionuclides, the corresponding figure is 0.58 μSv/h per unit activity concentration of ^{232}Th. The predicted dose rate from ^{40}K is 0.04 μSv/h per Bq/g. These dose factors have been applied to phosphate ore and phosphate rock using radionuclide activity concentrations selected from Appendix II and Appendix IV, respectively.[14] The results are given in Table 9. In Ref. [51] a mean dose rate of 0.54 μSv/h was calculated for 14 worldwide rock sources. Excluding an unrepresentative value for Tanzanian rock, the mean dose rate was 0.39 μSv/h. These values are consistent with those given in Table 9.

Gamma dose rates measured at two mines and beneficiation plants in the Syrian Arab Republic [52] are shown in Table 10. These results are very similar to the theoretical values reported in Table 9.

Extensive area monitoring using thermoluminescent dosimeters (TLDs) in rock tunnels used for transporting rock to a phosphoric acid plant in central Florida, USA, was carried out over a period of four years. The absorbed dose rates were in the range 0.08–3.4 μGy/h and rarely exceeded 1 μGy/h. The average absorbed dose rate was 0.18 μGy/h [53].

Gamma dose rates from phosphate ore can be summarized as follows:

(a) Dose rates associated with sedimentary material are generally a few tenths of a microsievert per hour, rarely exceeding 1 μSv/h, with the ^{238}U series radionuclides contributing almost the entire dose.
(b) Dose rates associated with igneous material are 0.1–0.3 μSv/h, significantly lower than those associated with sedimentary material. Material from Kola, Russian Federation, gives significantly lower dose rates than material from South Africa. About 60–80% of the dose is attributable to the ^{232}Th series radionuclides, with the ^{238}U series radionuclides contributing most of the balance.

[14] In order to demonstrate the relative contribution of all radionuclides, only data sets that included activity concentrations of ^{238}U and ^{232}Th series radionuclides as well as ^{40}K were selected from Appendices II and IV. Some ^{40}K concentrations were determined from the K_2O content given in Appendix IV.

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TABLE 9. GAMMA DOSE RATES NEAR LARGE VOLUMES OF PHOSPHATE ORE AND PHOSPHATE ROCK, PREDICTED FROM RADIONUCLIDE ACTIVITY CONCENTRATIONS

Source	Activity concentration (Bq/g)			Dose rate			
	U-238	Th-232	K-40	Total (μSv/h)	Contribution to total		
					U-238	Th-232	K-40
Material of sedimentary origin							
Phosphate ore:							
Sudan (Uro)	4.0 (Ra-226)	0.01	0.06	1.6	>99%	<1%	<1%
Sudan (Kurun)	0.4 (Ra-226)	0.01	0.14	0.2	95%	2%	3%
USA (central Florida)	0.8–3.1	0.02	0.003–0.019	0.3–1.2	98%	2%	<1%
Egypt	0.4	0.02	0.05	0.2	91%	8%	<1%
Phosphate rock:							
Morocco	0.9–1.9	0.01–0.03	0.03[a]	0.4–0.8	98%	2%	<1%
Togo	1.0–1.5	0.03–0.1	0.01–0.03[a]	0.4–0.6	93%	7%	<1%
USA (central Florida) (pebble)	1.3–2.5	0.03	0.03[a]	0.5–1.0	97%	3%	<1%
USA (central Florida) (concentrate)	0.7–1.8	0.02	0.03[a]	0.3–0.7	97%	3%	<1%
Egypt	0.4–0.5	0.02–0.04	0.02	0.2	92%	7%	<1%
Algeria	0.6	0.06	0.02	0.3	87%	12%	<1%
Jordan	0.8–1.0	0.002–0.02	0.01–0.15	0.3–0.4	98%	1%	<1–2%
Tanzania (Arusha)	4.1–4.6	0.61–0.63	0.29	2.0–2.2	83%	17%	<1%
Tunisia	0.8	0.03	0.03	0.3	95%	5%	<1%
Material of igneous origin							
Phosphate ore:							
Russian Federation (Kola)	0.07	0.1	0.1	0.1	31%	65%	4%
South Africa	0.2	0.4	0.003–0.02[a]	0.3	25%	75%	<1%

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TABLE 9. GAMMA DOSE RATES NEAR LARGE VOLUMES OF PHOSPHATE ORE AND PHOSPHATE ROCK, PREDICTED FROM RADIONUCLIDE ACTIVITY CONCENTRATIONS (cont.)

Source	Activity concentration (Bq/g)			Dose rate			
	U-238	Th-232	K-40	Total (μSv/h)	Contribution to total		
					U-238	Th-232	K-40
Phosphate rock:							
Russian Federation (Kola)	0.03–0.1	0.06–0.09	0.14	0.1	31%	60%	8%
South Africa	0.1–0.2	0.3–0.6	0.003–0.02[a]	0.2–0.4	18%	82%	<1%

[a] Estimated from the potassium content of the phosphate rock (see Table 51, Appendix IV).

TABLE 10. GAMMA DOSE RATES MEASURED AT TWO MINING AND BENEFICIATION FACILITIES IN THE SYRIAN ARAB REPUBLIC

Personnel	Al-Sharkeia mine		Khnefees mine	
	Occupancy (%)	Dose rate (μSv/h)	Occupancy (%)	Dose rate (μSv/h)
Mine workers	37	0.4	37	0.5
	3	0.3	3	0.3
	4	0.2	4	0.1
Plant workers	30	0.2	30	0.1
	15	0.3	10	0.3
			5	0.5
Administrative workers	46	0.1	41	0.1
Maintenance workers in workshops	30	0.1	30	0.1

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4.3.2.2. Inhalation of airborne dust

Measurements of airborne dust activity concentrations in sedimentary phosphate mining and beneficiation facilities in Florida, USA, are reported in Ref. [53]. Dust samples were collected on filters using either a high volume stationary air sampler or low volume personal air samplers. Alpha counting of the dust samples suggested an airborne ^{238}U activity concentration of 5–10 mBq/m^3 in the mining area. Higher dust levels, up to 100 mBq/m^3, were measured in the crushing, grinding and screening areas of the beneficiation plant. Although some of the dust levels were high, the occupancy periods of workers were reported to be only a small fraction of the total working period. In addition, workers were often required to use respiratory protective equipment as part of normal OHS procedures.

4.3.2.3. Inhalation of radon

Radon exposures were measured at two mining and beneficiation facilities in the Syrian Arab Republic [52], at mining and beneficiation plants in central Florida, USA [53], and in underground mines in Egypt [54, 55]. The results are summarized in Table 11. Assuming an equilibrium factor of 0.4 and an annual working period of 2000 h, the potential alpha energy exposures at Syrian facilities (0.3–1.1 mJ·h·m^{-3}) imply an annual average radon concentration of about 65–245 Bq/m^3. Elevated exposures of administrative workers at the Al-Sharkeia mine were reportedly caused by the offices being built on phosphate sands and being poorly ventilated, especially in winter. Remedial action in these particular workplaces was proposed. At benefication plants in Florida, USA, the radon concentrations in the flotation plant, pit cars and railcar loading area were consistent with indoor radon concentrations. Measurements were also made in mining and rock handling areas. With the exception of rock tunnels, background levels were not exceeded. The high radon and radon progeny concentrations measured in Egyptian underground mines were the result of poor ventilation.

4.3.3. Effective dose

4.3.3.1. Gamma radiation

Annual effective doses received by workers from external gamma radiation have been assessed using data from three countries and are summarized in Table 12. In the Syrian Arab Republic, doses received by workers in two sedimentary phosphate mining and beneficiation facilities have been determined from the dose rate

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TABLE 11. EXPOSURES TO RADON AND RADON PROGENY MEASURED AT PHOSPHATE MINING AND BENEFICIATION FACILITIES

Facility and location	Rn-222 EEC[a] (Bq/m^3)	Rn-222 activity concentration (Bq/m^3)	Mean annual potential alpha energy exposure ($mJ \cdot h \cdot m^{-3}$)
Syrian Arab Republic (Al-Sharkeia and Khnefees mines) [52]:			
Mines			0.4
Plants			0.5–1.1
Maintenance workshops			0.3
Administrative offices			0.4–1.1
Central Florida, USA [53]:			
Flotation plant, pit cars, railcar loading area		18.5–59.3	
Rock tunnels		214–1481	0.02–0.46
Egypt [54, 55]:			
Abu-Tartar mine	1800–5500		9
Safaga, Hamraween and ElQuser mines	1250–2700		

[a] Radon EEC (equilibrium equivalent concentration) is the activity concentration of radon in radioactive equilibrium with radon progeny that would have the same potential alpha energy concentration as the actual (non-equilibrium) mixture.

measurements reported in Table 10 [52]. In South Africa, doses received by workers in an igneous phosphate mining and beneficiation facility have been determined from measurements made with a portable gamma dose rate meter [56, 57]. In central Florida, USA, doses received by workers in sedimentary phosphate facilities have been determined from external exposure measurements using both lithium fluoride thermoluminescence dosimeters (LiF TLDs) and the more sensitive aluminium oxide carbon-doped luminescence dosimeters (Al_2O_3:C OSLDs) [53].

4.3.3.2. Inhalation of airborne dust

Annual effective doses received by workers from the inhalation of airborne dust are reported from facilities in South Africa and the USA and are summarized in Table 12. The doses were assessed from measurements conducted with personal air samplers (South Africa) or high volume stationary air samplers (USA).

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TABLE 12. DOSES RECEIVED BY WORKERS IN PHOSPHATE MINING AND BENEFICIATION FACILITIES

Worker location	Mean annual effective dose (mSv)		
	Gamma radiation	Inhalation of airborne dust	Total
Syrian Arab Republic (sedimentary phosphate) [52]:[a]			
Mine workers	1.3[b]; 1.6[c]		
Plant workers	0.8		
Administrative workers	0.4		
Maintenance workers in workshops	0.3		
South Africa (igneous phosphate) [56, 57]:			
Mining:			
Operational areas	0.42	0.70	1.12
Crushers	0.35	0.77	1.13
Workshops	0.09	0.58	0.66
Mine mobile equipment	0.66	0.51	1.17
Milling:			
Operational areas	0.10	0.19	0.29
Workshops	0.00	0.09	0.09
Beneficiation:			
Magnetic separation	0.05	0.19	0.24
Flotation operational area	0.23	0.09	0.32
Flotation workshop	0.67	0.09	0.76
Filtration operational area	0.05	0.27	0.32
Filtration workshop	0.00	0.09	0.09
Drying and storage	0.80	0.17	0.97
Dispatch	0.20	0.16	0.36
USA (sedimentary phosphate) [53]	0.168[d]; 0.095–0.114[e]	0.005–0.060	0.12–0.30[e]

[a] Doses from inhalation of airborne dust were not determined.
[b] Al-Sharkeia mine.
[c] Khnefees mine.
[d] Determined from LiF TLD measurements.
[e] Determined from Al_2O_3:C OSLD measurements.

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4.3.3.3. Total effective dose

For an igneous phosphate mining and beneficiation facility in South Africa, summing of the doses from external gamma exposure and inhalation of airborne dust gives total annual effective doses in the range 0.1–1 mSv (Table 12). The mean total annual effective dose received by workers in sedimentary phosphate mining and beneficiation facilities in Florida, USA, was calculated from measured exposure levels and found to be in the range 0.12–0.30 mSv [53]. In the mining area at this plant, 75% of the total dose arises from external exposure whereas in ore crushing, grinding and screening locations the reverse is the case, with the majority of the dose arising from internal exposure.

4.3.4. Transport of material

External gamma dose rates and annual doses received by workers involved in the transport of phosphate rock are reported in Refs [58, 59]. Doses received from external exposure to gamma radiation were calculated from exposure measurements and estimated maximum exposure periods. The results are shown in Table 13. With respect to sea transport, gamma dose rates arising from the loading of sedimentary phosphate rock originating from Morocco and Florida, USA, were found to be elevated above background levels, whereas the corresponding dose rates for igneous rock from Kola, Russian Federation (not shown), were not elevated. Dose rates for inland transport by ship were measured on a barge loaded with phosphate rock originating from Morocco and having activity concentrations at the upper end of the normal range. As expected, the highest doses were those arising from loading operations, owing to the closer proximity of the workers involved. Exposures during rail transport occur only while loading and unloading. Exposures for truck transport occur during loading and unloading and during transport as measured in the truck cab. The annual doses received by workers were all significantly less than 1 mSv.

4.4. PUBLIC EXPOSURE

Members of the public in the vicinity of phosphate rock mining and beneficiation operations may be exposed through the following pathways:

(a) Inhalation of dust and radon dispersed from the operations;
(b) Ingestion of groundwater contaminated with radionuclides migrating from the mining and tailings management facilities;

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TABLE 13. EXPOSURE OF WORKERS INVOLVED IN THE TRANSPORT OF PHOSPHATE ROCK [58]

Exposure situation	Dose rate (μSv/h)	Annual dose (mSv)
Sea transport, loading	0.10	0.09
Inland ship:		
Loading	0.26	
Transport	0.10	
Overall		0.18
Railway, loading and unloading	0.26	0.29
Truck:		
Loading and unloading	0.26	
Transport	0.16	
Overall		0.33

(c) Ingestion of foodstuffs affected by water and soil contamination through leaching and dust fallout;
(d) External gamma radiation from contaminated soil and bulk residues.

Exposure of members of the public, irrespective of the pathway involved, is likely to be very low because mining and beneficiation operations tend to be conducted at considerable distances from residential areas and involve materials with low activity concentrations. Most rock handling and processing operations are conducted under wet conditions. Under unfavourable wind conditions, it is possible for members of the public to be exposed to radionuclides in airborne dust generated by the crushing, milling and drying of rock. The migration of radionuclides from mining and residue management facilities into water bodies could result in the contamination of drinking water and food but, again, this exposure pathway is not expected to be significant, particularly because process water is usually recycled within the facility.

A study was conducted to determine if there was an elevated health risk due to ingestion of radionuclides (^{226}Ra and ^{210}Pb) or toxic metals (cadmium, lead and mercury) in fish harvested from lakes on previously mined lands in the central Florida phosphate region [60]. The study examined ten lakes in total:

(a) Four unreclaimed lakes (pit lakes that are formed when strip mining cuts fill with water and the site is abandoned for nature to recover with no attempt to reclaim the land);

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TABLE 14. ESTIMATED INCREMENTAL DOSE RECEIVED BY A MEMBER OF THE PUBLIC LIVING NEXT TO AN IGNEOUS PHOSPHATE MINING AND BENEFICIATION FACILITY [61]

Source of dose	Annual committed effective dose (rounded) (μSv)
Gamma radiation from soil	0.004
Inhalation:	
Airborne dust	16
Radon	1
Ingestion:	
Leafy vegetables	0.1
Root vegetables	0.3
Fruit	0.1
Meat	3
Milk	0.6
Cereals	0.1
Poultry	0.2
Eggs	0.07
Total	21

(b) Two reclaimed lakes (lakes created as part of the mining process that are contoured, vegetated and stocked with fish to resemble and function like natural lakes);
(c) Three natural lakes (lakes in the study area that were formed by natural means and regarded as 'control' lakes unaffected by mining);
(d) One reservoir (an artificially constructed lake that was unrelated to phosphate mining).

Six species of fish were sampled, representing those most commonly consumed by humans. The radionuclide data indicated no significant health risk attributable to the former mining activities. Radium is known to concentrate in bones, but the bones of fish are not normally consumed in the study region and so the risk from bones was largely discounted. There was no difference in lead or cadmium levels among the different types of lake. However, it was noted that mercury levels in fish from natural lakes were higher than in those from the mining-impacted lakes and may be due to the fact that natural lakes tend to be

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much older and have greater surface to volume ratios (more shallow areas), which provide more time and surface area to capture global fallout of mercury.

Another study in Florida, USA, surveyed radioactivity in food produced from a variety of land types, including mined lands (concentrating on lands which were reclaimed after phosphate mining) and unmined lands underlain with phosphate deposits [62]. More than 100 food samples were collected from 62 land parcels and analysed. This was followed by a study that investigated, more broadly, the presence of radioactivity in locally grown or caught foods, concentrating mainly on foods grown on reclaimed clay lands [63]. In extensive studies of foods grown on mined lands [62, 63], the doses were found to be trivial (less than 10 μSv/a).

Approximately 70 individual food samples were collected from five land parcels in the central Florida phosphate district and analysed for ^{226}Ra, ^{210}Pb and ^{210}Po. Corresponding soil samples were collected and analysed both for these radionuclides and for a variety of soil chemistry parameters. The results of the radioactivity and soil chemistry analyses of these samples were integrated into the database, which had been created from the initial study, and a variety of statistical analyses were conducted on this integrated data set [63]. The results of these analyses indicated that the concentrations of ^{226}Ra and ^{210}Pb in edible crops grown on mined phosphate lands were statistically higher than those in crops grown on unmined phosphate lands. However, the ^{210}Po concentrations were extremely low, with many being below the lower limit of detection, and the dose from food consumption was only a small fraction of that received by an average individual from other environmental sources of radioactivity. An individual who sourced all the sampled food types from the reclaimed clay land areas and all remaining food types from the general food pool was estimated to receive a committed effective dose of 191 μSv in a year from food consumption. By comparison, the corresponding ingestion dose received by an individual obtaining all food from the general food pool was estimated to be 164 μSv. Thus, the incremental ingestion dose attributable to the former mining operation was only 27 μSv per year. Two beef samples were analysed, one from mined land and one from unmined land. Each sample was replicated three times, yielding a total of six beef observations. The geometric mean values of ^{226}Ra activity concentration were 0.000147 and 0.000126 Bq/g for mined and unmined land, respectively. The difference between these results is statistically insignificant.

A dose assessment was conducted at an igneous phosphate mining and beneficiation facility in South Africa [61]. The assessment considered a member of the public residing on the perimeter of the facility, with all drinking water being obtained from an external source that was not influenced by the operation of the facility. The doses attributable to the operation of the facility were estimated from measurements of the concentrations of radionuclides in various

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environmental media, including surface water, groundwater and food, using conservative assumptions. The results are given in Table 14.

4.5. REGULATORY CONSIDERATIONS

In terms of the Standards, it is unnecessary to regulate (as a practice) material in which the activity concentrations of radionuclides in the uranium and thorium decay chains do not exceed 1 Bq/g. This criterion is of particular relevance to the mining and beneficiation of phosphate ore because the radionuclide activity concentrations in the materials involved are all rather moderate and may well be less than 1 Bq/g. Moreover, the nature of the processes involved is such that radionuclides do not become concentrated in scale and other deposits inside pipes and vessels, so the application of the 1 Bq/g criterion would generally require only a knowledge of the activity concentrations in the ore, phosphate rock and tailings.

4.5.1. Mining and beneficiation of phosphate ore of igneous origin

All radionuclide activity concentrations in the phosphate ore, phosphate rock and tailings are less than 1 Bq/g, implying that it is not necessary to regulate the mining and beneficiation of ore of igneous origin. This conclusion is supported by dose assessments which show that the annual effective doses received by workers and by members of the public do not exceed 1 mSv by any significant amount. The adoption of good OHS and environmental protection practices (not specifically aimed at radiological concerns) are likely to bring about further reductions in the already low levels of radiation exposure.

4.5.2. Mining and beneficiation of phosphate ore of sedimentary origin

While the activity concentrations of radionuclides in the ^{232}Th decay series in the phosphate ore, phosphate rock and tailings are all less than 1 Bq/g, the same is not always true of the radionuclides in the ^{238}U decay series. For those operations in which the activity concentrations of radionuclides in the ^{238}U decay series exceed 1 Bq/g, the doses received by workers and by members of the public need to be taken into account when considering the possible need for regulation as a practice. All indications are that in such situations, the doses arising from external gamma exposure and inhalation of airborne dust are unlikely to exceed 1 mSv. In those few instances where the ore is mined by underground methods, the radon concentrations to which the underground workers are exposed would have to be considered.

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It can be concluded that most mining and beneficiation operations involving material of sedimentary origin are candidates for exemption by the regulatory body, particularly if the operation is known to be conducted in accordance with good OHS and environmental protection practices. For some operations, a requirement for notification and even authorization in the form of a registration might be appropriate if there are concerns about airborne dust and contamination of water bodies. It may be necessary for the regulatory body to ensure that measures are in place to:

(a) Minimize airborne dust both inside and outside the plant;
(b) Control the way in which process water is managed; and/or
(c) Monitor the quality of nearby groundwater and surface water bodies.

In the case of underground mining, remedial action to reduce radon concentrations through improved ventilation might also be needed.

4.5.3. Transport of bulk material

The radionuclide activity concentrations of phosphate ore, phosphate rock and tailings are well below the levels at which the Transport Regulations would become applicable (see Section 3.1.3). Consequently, such material can be transported without any restrictions or controls of a radiological nature. This conclusion is supported by the results of dose assessments carried out for various transport scenarios.

5. PRODUCTION OF PHOSPHORIC ACID BY THE WET PROCESS

5.1. PROCESS DESCRIPTION

Digestion of phosphate rock with sulphuric acid is by far the most common type of wet process used for phosphoric acid production. Digestion with hydrochloric acid is used to a lesser extent for producing high purity phosphoric acid for use in foodstuff applications.

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5.1.1. Sulphuric acid digestion

5.1.1.1. Main process

A mixture of sulphuric acid and recycled phosphoric acid is added continuously to phosphate rock in a reactor vessel or 'attack tank'. The rock is digested by the sulphuric acid to produce phosphoric acid and calcium sulphate, known as phosphogypsum. Each tonne of P_2O_5 produced in the form of phosphoric acid is matched by 4–6 t of phosphogypsum (dry weight). The basic chemical reaction can be represented by:

$$Ca_3(PO_4)_2 + 3H_2SO_4 \rightarrow 3CaSO_4 + 2H_3PO_4$$

As the rock particles react, they tend to become coated with an insoluble layer of calcium sulphate, hindering further reaction. The presence of the recirculated phosphoric acid, as well as control over the rock particle size, minimizes this problem. The sequential chemical reactions are as follows:

$$Ca_3(PO_4)_2 + 4H_3PO_4 \leftrightarrows 3Ca(H_2PO_4)_2$$

and

$$3Ca(H_2PO_4)_2 + 3H_2SO_4 \leftrightarrows 3CaSO_4 + 6H_3PO_4$$

The chemical reaction for the digestion of fluorapatite may be expressed as follows:

$$Ca_{10}(PO_4)_6\,F_2 + 10H_2SO_4 + 20H_2O \leftrightarrows 10CaSO_4{\cdot}2H_2O + 6H_3PO_4 + 2HF$$

Following acid attack, the resulting phosphoric acid is transferred to one or more filtration assemblies, commonly of the tilting pan type (see Fig. 18), in order to separate the acid from the phosphogypsum.[15] The phosphogypsum is in a hydrated form, the degree of hydration depending on the process conditions, in particular the temperature, the P_2O_5 concentration and the free sulphate content. The main forms of phosphogypsum produced are the dihydrate form ($CaSO_4{\cdot}2H_2O$) and the hemihydrate form ($CaSO_4{\cdot}\frac{1}{2}H_2O$). After separation from

[15] Less commonly, either rotary table or travelling belt filtration is used.

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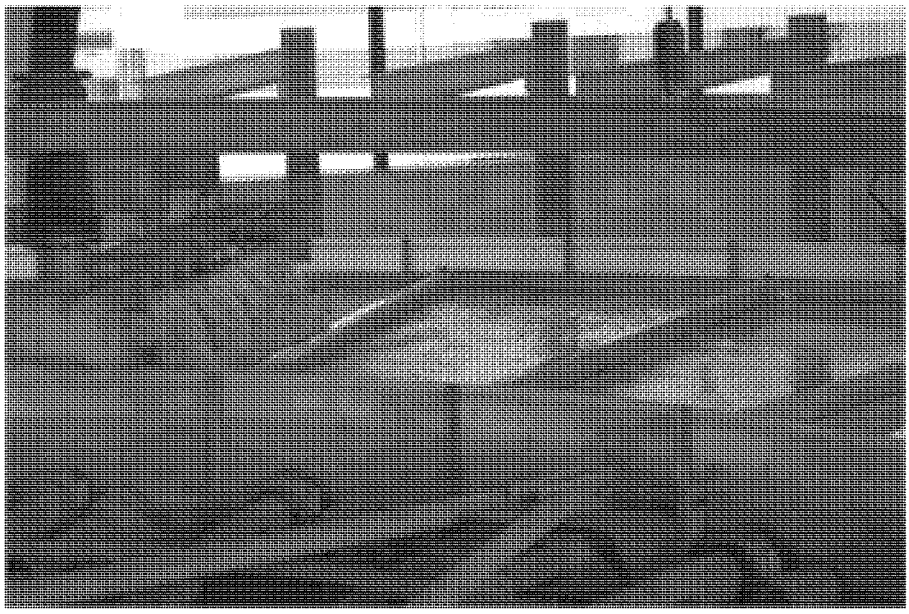

FIG. 18. Tilting pan filtration equipment.

the phosphoric acid, the wet phosphogypsum is sent to a residue pile (stack) for storage, usually after washing to remove traces of phosphoric acid and fluoride. The default condition for the subsequent use of phosphogypsum is the dihydrate form, since the hemihydrate and other hydrate forms convert rapidly to the dihydrate form. The rehydration process may begin even before separation from the phosphoric acid and the conditions for rehydration become more favourable still during washing and upon exposure to environmental moisture during transport and storage.

Several variants of the sulphuric acid digestion process are in commercial use [64] and are summarized in Appendix V. Each method has its advantages and disadvantages, with the choice of method in a particular situation depending on a variety of considerations, such as the complexity and cost of the processes and process equipment involved, the nature and level of experience of plant personnel, limitations on the quality and particle size of the feedstock material, the efficiency of P_2O_5 recovery and the quality of the phosphoric acid and phosphogypsum produced [65]. Most of the early phosphoric acid plants used one of the simpler methods based on dihydrate phosphogypsum production. The desire for improvements in energy efficiency, P_2O_5 recovery and phosphoric acid purity has led to a growth in popularity of methods based on hemihydrate

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phosphogypsum production, although these improvements have come at the cost of greater challenges for plant operators.

The compositions of the process materials are not easy to characterize in terms of origin or country since each manufacturing facility has its own strategy for obtaining phosphate rock feedstock, often depending on availability and economic factors. Heavy metals (such as arsenic, cadmium, chromium, lead and mercury) and fluoride originating from the ore become distributed between the phosphoric acid and phosphogypsum products, the exact distribution being very much dependent on the type of phosphate ore, the process and the type of impurity.

The phosphoric acid reactor is drained and cleaned periodically, typically annually. The thickness of the scale that accumulates on the walls of the reactor ranges from several centimetres to a metre or more. Scale may also accumulate on the roof of the tank, particularly near the point where the sulphuric acid is added. The scale consists predominantly of phosphogypsum and non-radioactive compounds such as sodium fluosilicate (Na_2SiF_6) and sodium potassium fluosilicate ($NaKSiF_6$). Removal of the scale is accomplished by high pressure water jetting and mechanical equipment.

The acid leaving the reactor contains residual minerals that are dissolved at saturation or supersaturation levels. These minerals are subsequently precipitated, leading to the accumulation of sediment and the deposition of radium rich scale on the relatively cool internal surfaces of pipes, vessels and filtration equipment. If allowed to build up, this sediment and scale can seriously reduce the flow capacity of pipes and interfere with the functioning of the filtration equipment. To help prevent this, the lines in a phosphoric acid plant are flushed every 1–2 weeks to purge the solids that have settled out and remove some of the scale adhering to the pipe walls. In addition, the filtration pans are periodically cleaned by dry chipping and abrasion and the filtration cloths that cover the tilting pans are replaced (see Fig. 19). Since flushing does not remove all the scale, some pipes affected by scaling are eventually replaced.

The buildup of residues such as scale in pipes and filtration equipment can be minimized by refinements to the production process [66]. As an example, in plants using the hemihydrate method (see Appendix V), scale formation can be eliminated by the incorporation of a simple hemihydrate rehydration step or by the addition of a small quantity of anti-scaling agent to the single stage filtration system.

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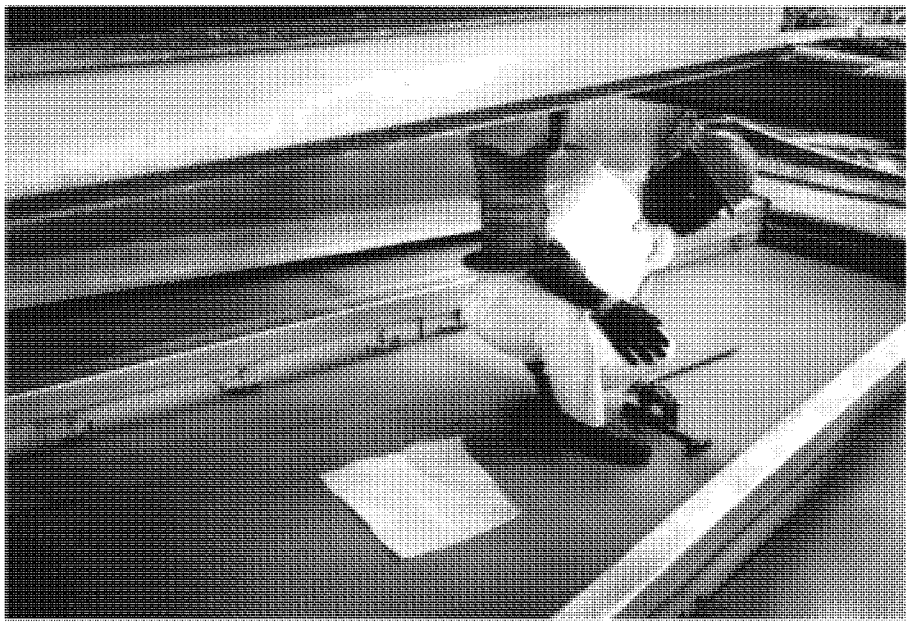

FIG. 19. Maintenance worker replacing the filter cloth on a tilting pan filtration assembly (courtesy: Florida Industrial and Phosphate Research Institute).

5.1.1.2. Further processing of phosphoric acid

Phosphoric acid emerging from the filtration step in any of the 'weak acid' methods (see Appendix V) has a P_2O_5 content in the range 24–36% and a typical residual solids content of some 2%. For most industrial applications, additional concentration and/or purification steps are required. First, the strength of the phosphoric acid is increased by evaporation to 40–55% P_2O_5. The design of the evaporation equipment takes account of the corrosive nature of the phosphoric acid and the very high scaling characteristics of the vapour released during the concentration process. The heat exchangers are fabricated from graphite or stainless steel, while the remaining equipment is made from rubber lined steel. An example of the acid composition at this stage, prior to further purification, is given in Table 15.

In many plants, a flocculant is then added to the acid and the solids are settled in a clarifier. At about 40% P_2O_5, the solubilities of residual fluosilicates and phosphogypsum are both at a minimum. As a result, many plants use this property to clarify the acid at the 40% level. The clarifier underflow contains, in

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TABLE 15. EXAMPLE OF PHOSPHORIC ACID COMPOSITION PRIOR TO PURIFICATION [48]

Main chemical constituents (%)		Trace elements (ppm)	
P_2O_5	55	Cl	175
MgO	2	As	14
Al_2O_3	0.05	Cd	2
Fe_2O_3	0.45	Cu	200
K_2O	0.04	Pb	1
Na_2O	0.05	V	20
SO_4^{2-}	3.18	Mn	250
F^-	0.28	Sr	2
		Cr	30

addition to fluosilicates and phosphogypsum, minor amounts of magnesium, aluminium and fluorine compounds and is sent back to the attack tank or to a separate filter for recovery of the remaining phosphate. Scale builds up on the walls of the 40% clarifiers and surge tanks. Since the buildup is slow, it does not require periodic removal. When the tanks eventually need to be relined, the scale is fully removed using a combination of high pressure water jetting and mechanical equipment.

Other purification methods such as solvent extraction, crystallization and ion exchange may also be used to remove impurities from the phosphoric acid. In the solvent extraction purification process, the H_3PO_4 is extracted by passing the crude acid through one or more organic phase extraction columns using a solvent such as a short chain (4–8 carbon atoms) alcohol, ketone, ether or amine. This technique removes 60–75% of the P_2O_5 contained as an impurity in the crude acid and converts it to H_3PO_4. The purified acid is then recovered in the backwash step using countercurrent extraction and concentrated to achieve the required P_2O_5 content.

Further concentration of phosphoric acid beyond 40–55% P_2O_5 causes various phosphates to precipitate. A typical formulation is $(Fe)_3NaH_{14}(PO_4)_8$, where aluminium can substitute for iron and ammonia and potassium can substitute for sodium, depending on availability [67]. These solids, which contain more than 50% P_2O_5, may be left suspended in the acid or may be removed by settling in a clarifier or by centrifuging, the choice being dictated by the final product specifications.

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The P_2O_5 content of phosphoric acid may be further increased by partially converting it from the orthophosphoric form (H_3PO_4) to polyphosphate forms, resulting in a product known as superphosphoric acid. The process involves a condensation reaction in which two or three orthophosphoric acid molecules are converted into higher polymeric forms. The basic chemical reactions are:

$$2H_3PO_4 \rightarrow H_4P_2O_7 + H_2O$$

and

$$3H_3PO_4 \rightarrow H_6P_3O_{10} + 2H_2O$$

The P_2O_5 content of superphosphoric acid is very high, exceeding even that of 100% orthophosphoric acid. Such high P_2O_5 concentrations are achieved by evaporating essentially all of the free moisture, including that generated in the condensation of the orthosphosphate, using high pressure evaporation units. The colour of superphosphoric acid is either light green ('green superphosphoric acid') or black ('black superphosphoric acid'), depending on whether the orthophosphoric acid from which it is derived has been manufactured from calcined rock or uncalcined rock, respectively. Most green superphosphoric acid is used for the manufacture of 10-34-0 liquid ammonium polyphosphate fertilizer, a product containing 60% $(NH_4)_3PO_4$ and 40% H_2O. The high polymeric content allows the sequestration of other cationic metals, such as iron, aluminium, magnesium and zinc. The product is often used to carry these micronutrients to the recipient crops. Black superphosphoric acid may either be sold as such for industrial uses or further processed by oxidation to produce green superphosphoric acid.

The production of superphosphoric acid typically begins with acid having a strength of 40–47% P_2O_5 that has been clarified to remove some of the magnesium, aluminium and fluorine compounds that precipitate out at that strength. After concentrating to a strength of 54% P_2O_5, the acid is fed into an alloy evaporator. Further concentration leads to the conversion of about 25–30% of the P_2O_5 content from the orthophosphate form to polyphosphate forms, giving a final product strength of at least 70% P_2O_5. In a variation of this process, several manufacturers in the USA use feed acid that has been subjected to minimal clarification and remove the impurities later in the process by subjecting the superphosphoric acid to pressure filtration. Scale formation occurs during the production of superphosphoric acid [68].

Figure 20 shows the scale inside a pipe in a green superphosphoric acid plant that was found to contain fluorine rich compounds, while Fig. 21 shows the

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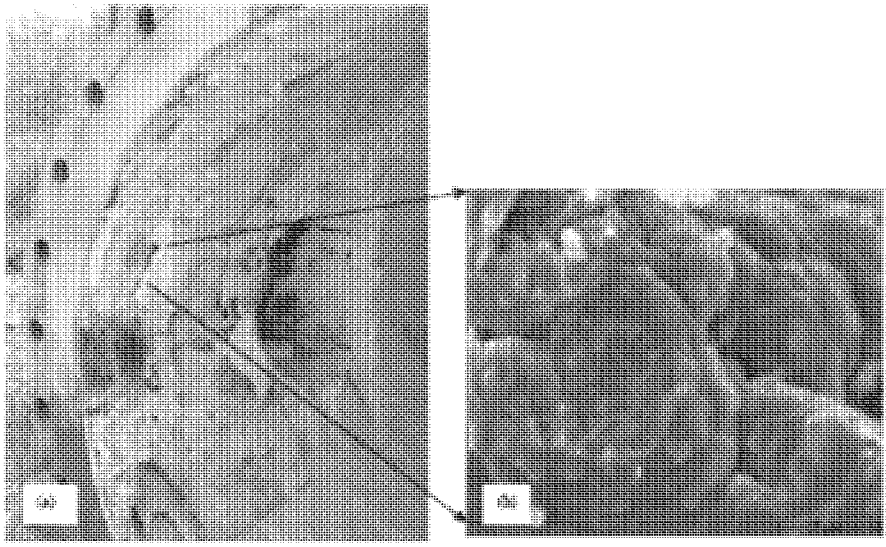

FIG. 20. Pipe scale observed in a green superphosphoric acid plant [68].

scale inside a green superphosphoric acid storage tank consisting primarily of calcium sulphate enriched in radium.

Phosphoric acid produced by the reaction of phosphate rock with sulphuric acid contains fluorine as hydrogen fluoride (HF), fluosilicic acid (H_2SiF_6), fluorosilicate salts (especially salts of Na and K) and metal fluoride complexes involving Al and Fe, making it unsuitable for use in certain applications, such as the production of animal feed supplements. There are several methods for reducing the fluorine content, of which the easiest and cheapest is generally to add reactive silica (diatomaceous earth) to convert the fluorine compounds into SiF_4 while concentrating the acid in a forced circulation evaporator to expel HF and SiF_4. Other methods of reducing the fluorine content include air stripping, steam stripping and concentration to superphosphoric acid followed by dilution back to orthophosphoric acid.

5.1.1.3. Management of residues

The scale removed periodically from the attack tank, which is predominantly non-radioactive, is transported by truck to the phosphogypsum stack.

Radium-bearing scale is removed from pipes, vessels and filtration equipment by abrasion or chipping and is usually sent to the phosphogypsum

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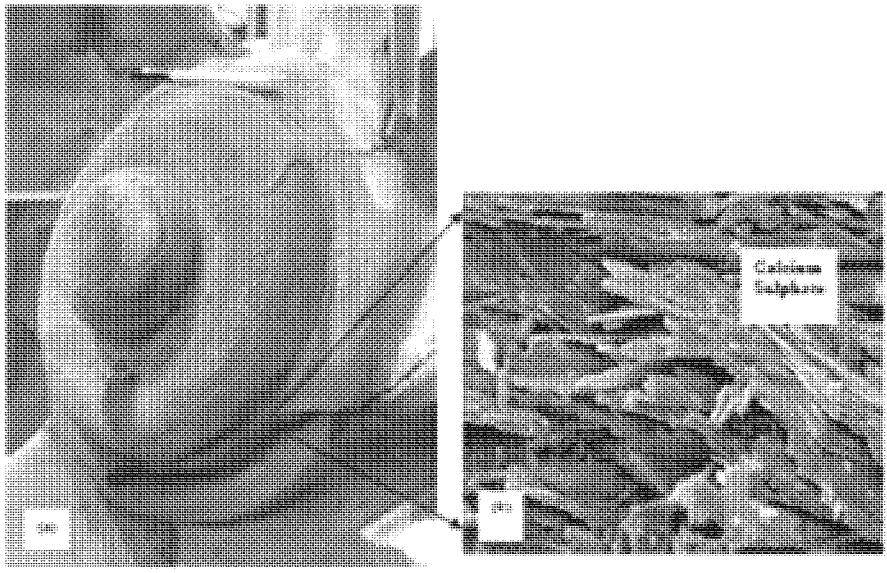

FIG. 21. Scale observed inside a green superphosphoric acid storage tank [68].

stack. The removal of scale in this way can cause localized site contamination that may subsequently need to be remediated. Alternatively, contaminated objects, particularly the filter pans and equipment, may be sent to off-site facilities for cleaning and refurbishing. This may result in the accumulation of radium-bearing scale at off-site premises.

The solid residues that settle out in the phosphoric acid clarification tanks are mixtures of very fine material comprising non-processed phosphate rock and non-filtered phosphogypsum [69]. They also contain fluosilicates and compounds of magnesium, aluminium and fluorine. This finding is supported by the following analytical results [70]:

(a) The concentrations of trace elements and Fe in the residues are similar to those found in the phosphate rock.
(b) The concentrations of Zn, Sr and Y are higher than the average values in normal sediments and soils.
(c) Elevated concentrations of Ca (14.2%, 19.3%), S (8.2%, 10.7%) and P (6.6%, 13.5%) are found in residues from plants in Senegal and Morocco, respectively.

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The residues are mostly recycled back to the attack tank or, in some cases, sent to the phosphogypsum stack.

When 40–55% phosphoric acid is purified using solvent extraction, the raffinate from the extraction process takes the form of a low grade acid containing the remaining P_2O_5. It may be used as a fertilizer provided that its cadmium content, which can be as high as 60–100 ppm, does not exceed local legal limits. Solvents can be recovered from the raffinate and the purified acid and recycled back to the process.

The concentration of acid beyond 55% generates suspended solids containing more than 50% P_2O_5. If these are removed, they are usually recycled back to the attack tank or used to make a low phosphate content fertilizer product such as MAP (see Section 6). Where a clarifier is used, the underflow may be sent to a filter and the phosphate-containing solids from this filter sent to the phosphogypsum stack. The solids that are separated out during the production of green superphosphoric acid also contain high concentrations of P_2O_5. They are used in the manufacture of other end products such as MAP fertilizer.

Rubber linings, where used, tend to become impregnated with radioactive material and are replaced periodically. The contaminated linings are sent to controlled disposal facilities specifically designed and authorized for the disposal of radioactive waste.

Process water used in various stages of the production process, including wastewater generated by the flushing of pipes, vessels and filtration equipment, is recycled by sending it to a large pond on the phosphogypsum stack for cooling and for settling or redissolution of solids before being returned to the process. Accordingly, process water is sometimes referred to as 'pond water'.

5.1.2. Hydrochloric acid digestion

Processes have been developed in Israel and the USA for the production of high purity phosphoric acid by the acidulation of phosphate rock with hydrochloric acid, although only the Israeli process has been practised commercially [71]. These processes have limited application and their environmental impact is reported to be in need of consideration [72].

A detailed description of the Israeli process, shown schematically in Fig. 22, is given in Refs [45, 73]. The dissolution of phosphate rock by hydrochloric acid results in an aqueous solution of primarily calcium chloride and phosphoric acid and the emission of hydrogen fluoride, according to the reaction:

$$[Ca_3(PO_4)_2]_3 \cdot CaF_2 + 20HCl \rightarrow 6H_3PO_4 + 10CaCl_2 + 2HF$$

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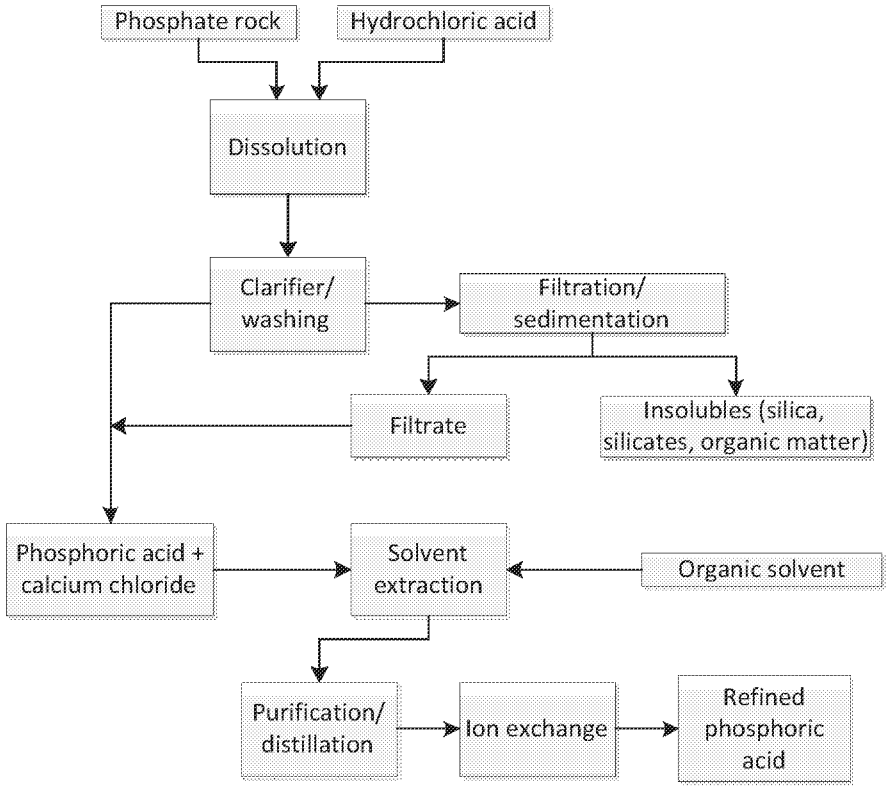

FIG. 22. Hydrochloric acid digestion process for the production of high purity phosphoric acid.

Other acid soluble components of the rock, such as $CaCO_3$, decompose simultaneously. The small amount of insoluble residue remaining comprises primarily silica, silicates and insoluble organic matter. This residue can be separated by filtration or by sedimentation in a thickener, followed by washing. The choice of method depends on economic considerations and on the precise nature of the residue.

Phosphoric acid is then selectively extracted from the dissolution liquor using a countercurrent organic solvent extraction process, leaving a calcium chloride brine containing most of the impurities, such as iron and fluorine. The brine is stripped with steam to recover any dissolved solvent. The brine is either disposed of in the sea or on land, depending upon site specific economic and environmental considerations. The solvent, now loaded with phosphoric acid, also contains trace amounts of Ca^{2+} ions and other impurities and is further purified by multistage countercurrent contact with isoamyl alcohol, normal

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butanol or a mixture of the two. The loaded solvent is then washed with a mixture of hydrochloric and phosphoric acids at controlled concentrations and stripped with water to recover the phosphoric acid. The stripped solvent, which is now almost completely acid free, extracts the remaining acids present in the raffinate and is recycled back to the extraction step. The phosphoric acid product contains some residual hydrochloric acid and dissolved solvent. The solution is concentrated to a P_2O_5 content of 69% in what is essentially a distillation process, during the course of which the residual hydrochloric acid and solvent are separated and recovered. The purity of the phosphoric acid so produced is much higher than that achievable from sulphuric acid digestion (see Section 5.1.1), although still not as high as that achievable from elemental (thermally produced) phosphorus (see Section 13).

5.2. RADIONUCLIDE ACTIVITY CONCENTRATIONS

5.2.1. Sulphuric acid digestion

Uranium is present in the phosphate rock primarily as the tetravalent ion U^{4+} and to a lesser extent the hexavalent ion U^{6+}. During the acid digestion process, ferrous iron readily reduces the U^{6+} present in the rock to U^{4+}. The reduction is also catalysed by fluoride ions originating from the rock. During acid filtration, contact with air results in oxidation to the hexavalent form and the uranyl ions complex mainly with phosphates. During the digestion process, 90–95% of the uranium in the phosphate rock migrates to the phosphoric acid [47], where it exists in the form of a uranyl phosphate complex and, to a lesser extent, uranyl sulphate and fluoride complexes. Uranium concentrations in phosphoric acid with a P_2O_5 content of 30% are given in Table 16 [45]. The remaining uranium in the phosphate rock migrates to the phosphogypsum, principally as a constituent of unreacted rock. Since ^{238}U and ^{234}U exist in the same chemical form, they remain in equilibrium during the digestion process.

Most of the radium in the phosphate rock migrates to the phosphogypsum. The exact amount depends on factors such as the process conditions and the characteristics of the phosphate rock. Percentages reported in the literature include 70–85% [47], 83.5% [74], 90% [75] and 92–93% [69]. Data on radioactivity levels in phosphogypsum are given in Section 10.3.

There are conflicting findings on the migration of lead during the digestion process. Some reports indicate that most or all of the lead in the phosphate rock migrates to the phosphogypsum, probably as poorly soluble lead sulphate [46, 76]. Other reports indicate that most or all of the lead migrates to the phosphoric acid [47, 75, 77].

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TABLE 16. URANIUM CONCENTRATIONS IN 30% PHOSPHORIC ACID [45]

Country	Concentration of uranium as U_3O_8 (%)
Algeria	0.013
Brazil	0.008
Israel	0.0165
Jordan	0.0165
Morocco	0.014
Tunisia	0.008
USA:	
Florida	0.019
North Carolina	0.008

Most of the polonium in the phosphate rock migrates to the phosphogypsum. Percentages reported in the literature include 78% [75], 99% [47], 87–94% [69] and more than 99% [78].

As with lead, there are conflicting findings on the migration of thorium during the digestion process. The behaviour of thorium seems to depend strongly on the process conditions and the characteristics of the phosphate rock. Thorium forms sparingly soluble salts with hydroxides, fluoride and phosphate, while sulphate compounds are relatively soluble.[16] Some studies have found that up to 75% of the thorium migrates to the phosphoric acid [79–81]. However, another study indicated that 80% of the thorium migrated to the phosphogypsum [75].

Radionuclide activity concentrations in phosphoric acid are given in Table 17. The ^{238}U activity concentrations vary over a wide range (0.14–2.6 Bq/g). The activity concentrations of ^{238}U can also be determined from the uranium concentrations in Table 16 by assuming that 1 g of U_3O_8 contains 12 347 Bq of ^{238}U. The activity concentrations determined in this way (in this case for 30% phosphoric acid) are similar to those reported in Table 17 but confined to a narrower range (1.0–2.3 Bq/g). The activity concentrations of radionuclides other than ^{238}U are, as expected, generally much lower.

Radionuclide activity concentrations in residues from phosphoric acid production are given in Table 18. In most cases, the activity concentrations are moderate (up to a few becquerels per gram). In some scales, however,

[16] The predominant complexes are expected to be fluoride, phosphate and sulphate.

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TABLE 17. RADIOACTIVITY IN PHOSPHORIC ACID (BY COUNTRY)

Location of plant	Phosphate rock feedstock		Activity concentration (Bq/g)								Reference
	Origin	Type	U-238	Th-230	Ra-226	Pb-210	Po-210	Th-232	Ra-228	Th-228	
Belgium	Not reported	Sedimentary and igneous	0.65		<0.005			<0.005			[85]
Morocco	Morocco	Sedimentary	0.74	0.16	—	0.005	0.001	0.001			[86]
Netherlands	Not reported	Sedimentary and igneous	1.4		0.074						[87]
South Africa	South Africa	Igneous	0.17 (0.14–0.19)		<LLD[a]	0.14–0.18[b]		0.39 (0.28–0.47)	<LLD	0.25 (0.13–0.41)	[48]
Spain	Morocco	Sedimentary	1.07–1.83	0.1–0.2	0.006–0.008	0.078–0.109		0.01–0.05	<LLD	0.004–0.013	[46, 88]
Spain	Kola	Igneous	0.10–0.16	0.02–0.03	<LLD	<LLD		0.01–0.02	0.002	0.01–0.03	[46]
USA	Central Florida	Sedimentary	0.23–2.6	0.25	0.004–0.015			0.004			[16, 47]
USA	Northern Florida	Sedimentary	0.26		0.0074						[47]
Not reported	Morocco	Sedimentary	2.44 (2.28–2.58)		0.004–0.011						[74]

[a] LLD: Lower limit of detection.
[b] Derived from values for phosphate rock (Appendix IV) and phosphogypsum (Appendix VI).

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TABLE 18. RADIOACTIVITY IN RESIDUES FROM PHOSPHORIC ACID PRODUCTION

Residue	Location of plant	Type of feedstock	Activity concentration (Bq/g)						Reference
			U-238	Ra-226	Pb-210	Th-232	Ra-228	Th-228	
Scale:									
Attack tank	South Africa	Igneous	3.51	4.47		11.0	8.80	9.46	[48]
Attack tank	Northern Florida, USA	Sedimentary	0.14	0.83					[48]
Filtrate tank	Central Florida, USA	Sedimentary	1.0	14					[47]
Pipes, vessels, filters	Central Florida, USA	Sedimentary		3700					[82]
Washing acid section	Netherlands	Sedimentary and igneous		4–4000					[87]
Concentrator	South Africa	Igneous	0.079	0.086		0.983	0.424	1.48	[48]
Flash cooler	South Africa	Igneous	0.56	0.85		1.71	2.30	2.01	[48]
Circulation vessel	South Africa	Igneous	0.066	0.07		0.918	0.414	0.96	[48]
Phosphoric acid plant	UK	Sedimentary	<LLD[a]–2.84	0.03–2.42	0.19–4.55		Insignificant		[68]
Green superphosphoric acid plant piping	UK	Sedimentary	0.04–8.62	0.03–0.38	<LLD–0.12		Insignificant		[68]
Green superphosphoric acid storage tanks	UK	Sedimentary	0.21–0.48	5.27–11.11	0.96–11.55		Insignificant		[68]
Pipe scales	Spain	Sedimentary	0.98	1.41	2.03			0.02	[46]
Sediment, filtrate tank	Central Florida, USA	Sedimentary	<0.037	2.4–3.1					[47]
Sludge, filtration/washing	Huelva, Spain	Sedimentary	0.91–1.23	1.31–4.30	1.42–1.90	0.01–0.03	0.02–0.07	0.01–0.03	[88]
Filter cloths/residues	Huelva, Spain	Sedimentary	0.29–0.57	2.11–3.34	1.03–2.33			0.03–0.05	[46]
Raffinate	Not reported	Sedimentary and igneous	2.2	< 0.005		0.08			[48]

[a] LLD: Lower limit of detection.

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^{226}Ra activity concentrations as high as 4000 Bq/g have been found. The activity concentration of ^{226}Ra in scale deposited on the internal surfaces of pipes, vessels and filtration equipment can reach as high as 3700 Bq/g [82–84].

5.2.2. Hydrochloric acid digestion

While this process has been well studied, little is known about the fate of the radionuclides introduced via the phosphate rock feedstock. The chemical conditions suggest that all the radionuclides, including uranium and radium, dissolve in the hydrochloric acid with only trace quantities remaining in the residue consisting of small amounts of silica, silicates and insoluble organic matter. The subsequent solvent extraction step is not likely to extract any of the radionuclides, leaving them in the calcium chloride raffinate. Radium, in particular, is chemically similar to calcium. However, even if the raffinate is evaporated to dryness, the radionuclide activity concentrations will be less than those in the phosphate rock feedstock because of the increase in mass. The phosphoric acid product is expected to contain negligible amounts of uranium and other radionuclides after the extraction and purification steps, but may contain some residual thorium.

In this process, hydrochloric acid is recovered from the phosphoric acid in the evaporators. Since radionuclides are dissolved in the hydrochloric acid, evaporators could be possible points of contamination, activity buildup and exposure. The mixing tanks used for recycling of hydrochloric acid could also be subject to contamination and activity buildup over time.

5.3. OCCUPATIONAL EXPOSURE

Most phosphoric acid production plants use the sulphuric acid digestion method and the information on occupational exposure given in this section is mostly related to this method.

5.3.1. Exposure pathways

The potential for significant occupational exposure occurs mainly in work activities associated with the handling of phosphate rock feedstock and the operation and maintenance of filtration equipment used for acid–phosphogypsum separation [89]. External exposure to gamma radiation is one of the main exposure pathways and is likely to be of concern in the following areas and activities:

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(a) Feedstock rock handling;
(b) Attack tank mixing compartments and agitators;
(c) Filtration equipment, in particular, scale laden pipes, distributors for rotating tilting pan filters and operating filter pans;
(d) Acid clarification and storage, in particular, clarification and storage tanks containing settled sludge;
(e) Equipment maintenance, in particular, exposure to radium rich scale during activities such as the replacement of pipes, the cleaning of evaporator heat exchangers, the repair of filter cloths and the mechanical removal of filter pan scale by chipping and abrasion.

The other main exposure pathway is via inhalation of radionuclides in airborne dust. This is likely to be of concern in the following areas and activities:

(a) Feedstock rock handling;
(b) Attack tank maintenance;
(c) Filtration equipment during repeated filtration and washing;
(d) Equipment maintenance, in particular, activities involving dry material such as filter pan scale chipping.

Exposure via the inhalation of radon is only likely to be of concern in highly enclosed and poorly ventilated areas in which process material is stored or handled. The tunnels within which phosphate rock is conveyed from storage areas to the processing plant ('rock tunnels') could represent such a situation if not adequately ventilated (see Table 11). In all other working areas, there is little potential for significant accumulations of radon to occur.

In the case of plants using the hydrochloric acid digestion method, exposures of workers are expected to occur mainly in the solid residue and scale handling areas.

5.3.2. Exposure levels

5.3.2.1. Gamma dose rates

Gamma dose rates during routine plant operation have been measured in workplaces at several phosphoric acid production plants and the reported values are summarized in Table 19. In most cases, the incremental gamma dose rates in phosphoric production plants in normally occupied areas are less than 0.2 μSv/h but may attain 2 μSv/h close to concentrated acid tanks or filtration systems.

Gamma dose rates can be higher during maintenance operations. The highest dose rates are likely to be those associated with the buildup of radium rich scale

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TABLE 19. GAMMA DOSE RATES IN PHOSPHORIC ACID PRODUCTION PLANTS

Location	Average incremental dose rate (μSv/h)
Spain (during processing of rock from Morocco and Kola) [46]:	
Digestion area	0.03–0.06
Filtration system at washing steps	0.4–1.1
Milling area	0.02–0.4
Phosphoric acid concentration and storage areas	0.01–0.5
Islamic Republic of Iran (workplaces (measurements over a six month period using TLDs)) [90]	0.05–2.7
Poland (phosphoric acid production areas) [91]	0.08–0.24
Germany [87]:	
Several phosphoric acid plants	0.1–1.9
Production halls, acid collection tanks (worker occupied areas)	0.2

within equipment [92]. This occurs primarily in the phosphogypsum filtration system. In tilting pan filtration equipment, scale builds up in the pans, filter cloths, central filtrate distribution system and piping and can give rise to absorbed dose rates of up to 75 μGy/h on contact during normal operation [89]. Piping between the attack tank and the phosphogypsum filtration area can also accumulate radium rich scale [53]. Some of this piping can give rise to dose rates of 100 μSv/h, as measured on contact with the pipes in the maintenance workshops. Similarly, the filtration assembly, especially underneath the filters near the distribution hub, can produce dose rates on contact in the range 100–120 μSv/h during maintenance [92].

Gamma exposure data have been reported for maintenance activities in South African phosphoric acid plants processing phosphate rock of either igneous origin or 75% igneous and 25% sedimentary origin [48]. The results are summarized in Table 20. It is evident that the highest dose rates are those associated with maintenance work inside the flash coolers.

5.3.2.2. Airborne dust

Airborne dust measurements were carried out in a phosphoric acid plant in Huelva, Spain [93]. The ^{238}U, ^{230}Th and ^{232}Th airborne activity concentrations

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TABLE 20. EXPOSURE TO GAMMA RADIATION DURING PLANT MAINTENANCE ACTIVITIES [48]

Plant	Annual exposure period (h)	Average dose rate (μSv/h)
Attack tanks:		
General internal maintenance	60	0.58
Manual scale removal	78	0.58
Flash coolers:		
General internal maintenance	16	1.5
Manual scale removal	48	1.5
Concentrators:		
General internal maintenance	70	0.58
Erection of internal scaffolding	10	0.4
Circulating vessels:		
Manual scale removal	16	0.5

were 0.3, 0.2 and 0.1 mBq/m^3, respectively, for an average mass concentration of 0.37 mg/m^3. Gross alpha and beta activity concentrations determined in airborne dust in phosphoric acid production plants in Florida, USA, are reported in Ref. [53]. The alpha activity concentrations were 40–70 mBq/m^3. Airborne dust inhalation does not appear to be a significant exposure pathway in wet process phosphoric acid production facilities.

5.3.2.3. Inhalation of radon

Radon and radon progeny concentrations were measured in plants in Huelva, Spain [94] and in central Florida, USA [53]. Under normal operating conditions, concentrations were found to be similar to background levels. This included the rock tunnels at the plants in Florida, where the potential alpha energy concentration of radon progeny was found to be consistently less than 0.02 μJ/m^3. The radon progeny concentration was also measured in rock tunnels under abnormal conditions, that is, after a long period with the ventilation fans not in operation. Although the potential alpha energy concentration was found to have increased, it still did not exceed 0.2 μJ/m^3. Assuming an equilibrium factor of 0.4, this potential alpha energy concentration is equivalent to a radon gas

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concentration of the order of 100 Bq/m^3. Although this is higher than the worldwide average indoor radon concentration, it is not uncommon for such a level to be found in many homes and the occupancy period of the worker is, in any case, very short in comparison. Consequently, it can be concluded that the inhalation of radon is not a significant exposure pathway.

5.3.3. Effective dose

5.3.3.1. Gamma radiation

Most modern phosphoric acid plants incorporate a high degree of automation, which minimizes exposure periods in areas of high dose rates during normal operation. During maintenance operations inside process vessels, dose rates may be higher but, again, the annual exposure periods are short. Assessments of the annual effective doses from gamma radiation received by workers at various phosphoric acid plants around the world can be summarized as follows:

(a) In central Florida, USA, doses were assessed using individual monitoring of workers by means of LiF TLDs and the more sensitive Al_2O_3:C OSLDs [53]. The radionuclide activity concentrations in the phosphate rock feedstock (of sedimentary origin) were about 1.4 Bq/g for the ^{238}U decay series and less than 0.03 Bq/g for the ^{232}Th decay series.

(b) Doses received by workers at four phosphoric acid plants in Poland were assessed using a pressurized ion chamber and LiF TLDs deployed at fixed locations [91]. The phosphate rock feedstock was of sedimentary origin, imported from northern Africa (Morocco, Tunisia and Algeria), the USA and the Middle East. The activity concentrations of the radionuclides in the ^{238}U decay series were typically about 1.5 Bq/g.

(c) Doses were assessed using a gamma dose rate meter and measured occupancy periods at a plant in Spain. The plant was processing rock of sedimentary origin imported from Morocco and igneous rock imported from Kola, Russian Federation [46].

(d) Doses received during maintenance work inside process vessels were assessed at plants in South Africa, using the average dose rates and annual exposure periods given in Table 20. The origin of the phosphate rock feedstock was either igneous or a mixture of 75% igneous and 25% sedimentary [48].

The results of these assessments, which are summarized in Table 21, suggest that the workers receiving the highest annual doses (up to 0.35 mSv)

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TABLE 21. DOSES RECEIVED BY WORKERS FROM EXPOSURE TO GAMMA RADIATION IN PHOSPHORIC ACID PLANTS

Worker category	Mean annual effective dose (mSv)
Workers handling phosphate rock feedstock:	
Central Florida, USA [53]	0.194–0.300
Four plants in Poland [91]	0.05
Phosphoric acid production workers:	
Central Florida, USA [53]	0.264–0.348
Huelva, Spain [46]	0.135–0.212
Maintenance workers, South Africa [48]:	
General maintenance inside attack tanks	0.035
Manual scale removal inside attack tanks	0.045
General maintenance inside flash coolers	0.024
Manual scale removal inside flash coolers	0.072
General maintenance inside concentrators	0.041
Erection of scaffolding inside concentrators	0.004
Manual scale removal inside circulating vessels	0.008
Service workers working mainly off-site on the repair of pumps, filter pans and other equipment, central Florida, USA [53]	0.066–0.175

work in the attack tank and filtration areas. The doses received by workers engaged in the handling of phosphate rock feedstock are lower, while maintenance workers and service personnel receive the lowest doses.

5.3.3.2. Airborne dust

The dose from inhaled airborne dust was assessed during routine operation in a phosphoric acid production plant in the Islamic Republic of Iran [90] by air sampling and alpha activity measurements. The average internal dose for the plant was 0.14 mSv/a, with a range of 0.04–0.33 mSv/a across different workplaces. The maximum inhalation dose was found in phosphate rock bulk storage areas.

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Results for phosphoric acid plants in Florida, USA, were published as dose distributions [53]. The most probable doses were <0.05 mSv/a for workers handling phosphate rock feedstock and <0.02 mSv/a for workers engaged in the actual phosphoric acid production process.

5.3.3.3. Total effective dose

Summing the dose values given in Sections 5.3.3.1 and 5.3.3.2 gives total annual effective doses of about 0.1–0.3 mSv for workers handling phosphate rock feedstock and 0.3–0.4 mSv for workers involved in the main phosphoric acid production process. For a plant in the Islamic Republic of Iran, the annual effective dose to workers, averaged over all workplaces, was 0.78 mSv.

Little information is available on doses received by workers in plants using hydrochloric acid digestion. The indications are that the doses from gamma exposures and radon inhalation are well below 1 mSv/a [95].

5.3.4. Measures to reduce doses

The undertaking of regular gamma surveys and the education of workers are examples of measures that, at a relatively low cost, have proven to be effective in ensuring that workers do not spend unnecessary time in areas of high gamma dose rates. Where the nature of the work requires workers to spend time close to high activity material such as radium rich scale in filtration equipment, the use of shielding has enabled doses to be reduced. Measures taken to minimize the formation of scale for purposes of maintaining plant performance (see Section 5.1.1.1) have the added advantage of minimizing workers' exposure to gamma radiation.

Various approaches have been used to minimize the doses received by workers via the inhalation of airborne dust. These include improvements in the design of process equipment, the adoption of measures to reduce the spillage of material and the installation of equipment to control airborne dust levels. The growing use of wet grinding of the phosphate rock feedstock instead of the more traditional dry grinding methods is particularly effective in reducing doses arising from dust inhalation, since wet grinding techniques do not generate any airborne dust. There is also no misting from wet grinding as it takes place inside the mill.

5.4. PUBLIC EXPOSURE

There is little potential for members of the public to receive significant exposures from phosphoric acid production facilities. The activity concentrations

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in bulk materials are moderate and exposure to gamma radiation outside the site boundary can be expected to be negligible. Phosphoric acid plants are potential sources of airborne dust containing radionuclides. However, this dust tends to become rapidly deposited in the vicinity of the source and is unlikely to be transported to nearby residential areas. This has been confirmed by airborne dust monitoring around plants in central Florida, USA [96]. There is also little potential for public exposure via contamination of surface water bodies. Process water is generally recycled from the phosphogypsum stacking system back to the acidulation process. Normal environmental protection requirements will generally ensure that any water that is discharged from the facility is treated to reduce contaminant concentrations (including radionuclide concentrations) to acceptable levels.

The phosphogypsum stacks themselves are potential sources of public exposure. More details are provided in Section 10.4.

5.5. REGULATORY CONSIDERATIONS

Radionuclide activity concentrations in many of the process materials may exceed 1 Bq/g, with values sometimes reaching a few becquerels per gram in bulk materials (phosphate rock feedstock, phosphoric acid and phosphogypsum) and, occasionally, a few thousand becquerels per gram in the scale that accumulates inside pipes, vessels and filtration equipment. In terms of the Standards, therefore, wet process phosphoric acid production needs to be considered for regulation as a practice.

Evidence suggests, nevertheless, that doses arising from exposure to these materials are not high enough to be of serious concern. Annual doses received by workers are less than 1 mSv, while members of the public are unlikely to receive any significant dose. Consequently, it is expected that regulatory control would be limited to just a few basic requirements, with authorization in the form of a registration probably being the most appropriate regulatory option. During routine plant operation, the regulatory body would need to be satisfied that good OHS and environmental protection practices (including control of discharges) are being followed, that reasonable efforts are being made to ensure that doses remain below levels of concern and that exposure conditions in the workplace are reviewed as appropriate, for instance, if circumstances change. During non-routine operations, procedures would need to be in place to ensure that the doses received by maintenance workers, especially those engaged in the removal and handling of scale, remain below levels of concern. The scale itself would need to be disposed of at an approved hazardous waste facility.

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With the exception of some of the scales removed from pipes and vessels during maintenance operations, the radionuclide activity concentrations in all the process materials are such that the Transport Regulations would not apply to these materials during transport.

6. MANUFACTURE AND USE OF AMMONIUM PHOSPHATE FERTILIZERS

Ammonium phosphates are a class of predominantly granular fertilizers produced by reacting phosphoric acid with ammonia. These fertilizers have a high nutrient content and convenient handling characteristics. They combine, in a single application, the two essential fertilizer ingredients, nitrogen and phosphate, in proportions favoured by the agricultural market and are referred to generically as NP fertilizers. The addition of potassium during the manufacturing process results in the production of NPK fertilizers. The favourable characteristics of ammonium phosphate fertilizers result in them being by far the most widely traded phosphate fertilizers worldwide [45]. There are two basic types of ammonium phosphate fertilizer:

(i) MAP, typically containing 10–11% N and 50–52% P_2O_5;
(ii) DAP, typically containing 18% N and 46% P_2O_5.

The primary emphasis of commercial production is increasingly on DAP.

6.1. PROCESS DESCRIPTION

6.1.1. Main process

MAP and DAP are produced by the reaction of phosphoric acid with ammonia. As phosphoric acid is tribasic (that is, having three replaceable hydrogen ions), it can form monoammonium, diammonium or triammonium phosphate salts, depending on the number of hydrogen ions replaced by ammonium ions (NH_4^+). Thus, the replacement of only one hydrogen ion produces MAP ($NH_4H_2PO_4$), while the replacement of two hydrogen ions produces DAP ($(NH_4)_2HPO_4$).

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The primary reactions are:

$$H_3PO_4 + NH_3 \rightarrow NH_4H_2PO_4$$

and

$$NH_4H_2PO_4 + NH_3 \rightarrow (NH_4)_2HPO_4$$

Triammonium phosphate is unstable in ambient conditions, rapidly losing ammonia and reverting to the stable diammonium phosphate form. The production process for MAP and DAP fertilizer products consists of a 'pre-neutralization' step, using either a conventional reactor or a 'pipe cross reactor', followed by a granulation step. The ammoniation reaction is exothermic, with the reaction temperature reaching 115–120°C. During the granulation process, a potassium salt may be added, resulting in the production of NPK fertilizer.

In the conventional pre-neutralizer reactor method, ammonia (anhydrous liquid ammonia or, in some cases, ammonia gas or a gas–liquid mixture) is added to phosphoric acid, increasing the ammonia:acid mole ratio and causing the acid to become partially neutralized. Usually, 65–70% of the total phosphoric acid requirement is fed to the pre-neutralizer in the form of clarified acid (52–54% P_2O_5). The use of clarified acid ensures that it is free of any iron or aluminium phosphate impurities, these being undesirable because they cannot be ammoniated. The balance of the acid requirement may be provided in the form of relatively unclarified 28% P_2O_5 acid although, with a decline in quality of some phosphate rock feedstocks, clarified acid may be preferred in some situations. The balance of the acid requirement may also be provided in the form of scrubber liquor extracted from the scrubber system, containing 20–30% P_2O_5. The degree of ammoniation is carefully controlled to produce a slurry with an ammonia:acid mole ratio of 0.5–0.7 for MAP production and 1.3–1.4 for DAP production.[17] The slurry is then introduced to a granulator for further ammoniation and production of granular product (see Fig. 23). The slurry is distributed on a bed of recycled undersized ammonium phosphate product while the remaining ammonia required for completion of the reaction is introduced from below the bed. Granulation occurs by agglomeration and coating of the recycled MAP or DAP particles with the appropriate slurry. This final stage of the ammoniation reaction is controlled to a mole ratio of 1.0 for MAP production and 1.90–1.95 for DAP production.

[17] In some facilities, MAP is produced by a 'back titration' method, in which a 1.3–1.4 mole ratio (DAP) slurry is first generated and then more acid is added to lower the ratio to the required 0.5–0.7 range.

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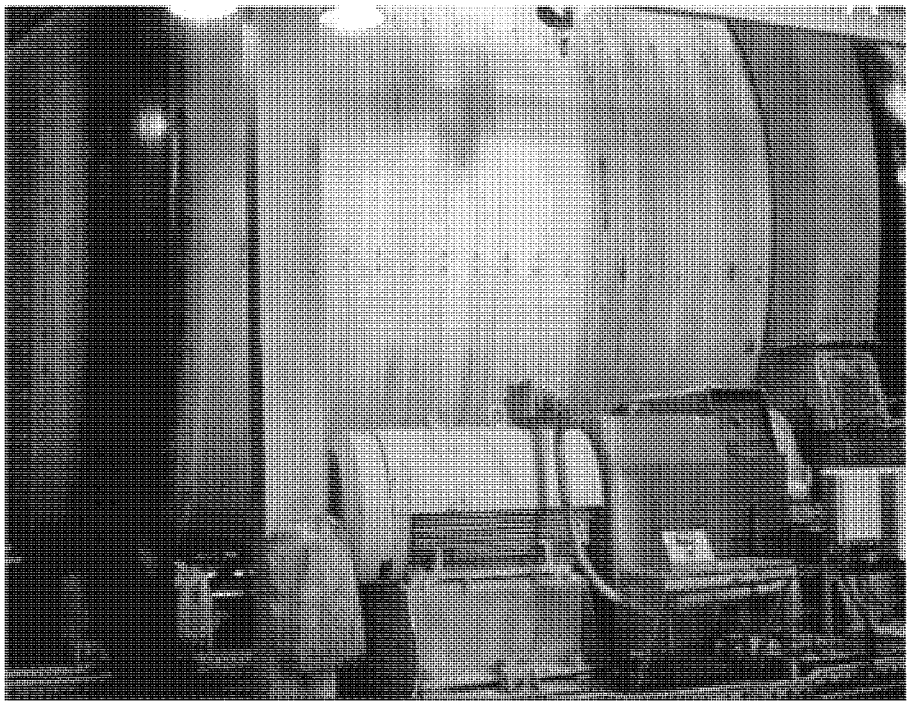

FIG. 23. Rotary drum ammoniator–granulator (courtesy: Florida Industrial and Phosphate Research Institute).

As an alternative to the conventional pre-neutralizer reactor method, the pipe cross reactor method is being used to an increasing extent, since it offers various technical and commercial advantages, including reduced energy consumption. A length of pipe incorporating a pipe cross or pipe tee is installed within a rotary drum granulator. Ammonia is introduced into the cross or tee in the direction of the horizontal axis. Phosphoric acid is introduced through the mixer head in a direction perpendicular to the flow of ammonia. The reaction between the ammonia and the phosphoric acid is continued to the point of producing MAP, which is then discharged as a melt or slurry inside the granulator.

The granulated product, containing 2–3% water, is dried using hot air in a co-current rotary drum dryer. The dried product is then screened to separate out grains in the size range 1–4 mm. The precise size of grain produced depends on market requirements. The product is conveyed to a rotary drum cooler, where it cools from 70°C to about 40°C, and is then conveyed to a storage building. Oversize and undersize material from the screening step, together with residual on-size material, are recycled back to the granulator after pulverizing where necessary. In the

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FIG. 24. Storage warehouse — product delivered by conveyor system (courtesy: Florida Industrial and Phosphate Research Institute).

post-granulation stage, the product is coated with, for example, vegetable oil to prevent airborne dust generation before being conveyed to the storage bins. In preparation for shipping, the granulated products are moved to storage areas by conveyors or by workers using large mobile equipment (see Figs 24 and 25). Workers collect spillages using smaller equipment or by hand with shovels. The products are shipped in bags, trucks, freight cars (see Fig. 26), barges or large ocean-going ships. MAP generally offers two NPK fertilizer grades: 11-52-0 and 10-50-0, the numerical values referring to the relative proportions of total nitrogen, minimum phosphate (as available P_2O_5) and potash (K_2O), respectively. DAP has a nominal NPK grade of 18-46-0. The fertilizers are applied to the soil using conventional dry fertilizer spreaders.

6.1.2. Management of residues

The production of fertilizer generates residues within the processing equipment. Typically, these are flushed out at intervals of 2–4 weeks and sent to

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FIG. 25. Storage warehouse — payloader for shipping (courtesy: Florida Industrial and Phosphate Research Institute).

the process water recycling system, which may form part of the water management system for phosphoric acid production.

There is always some spillage of dry product during production. While every attempt is made to return spillage to the production process, sometimes the presence of water makes this impractical. In that event, spillages are flushed with process water and the material sent to the process water recycling system. If the spill is large, it may also be transported by a separate vehicle or conveyor to the process water recycling system or to a nearby phosphogypsum stack.

Sources of gaseous emissions from the production of ammonium phosphate fertilizer include the reactor, granulator, dryer and cooler, as well as product sizing and material transfer operations [97]. Gaseous emissions are typically treated in the following manner, although variations exist from plant to plant:

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FIG. 26. Loading of fertilizer product into a railcar (courtesy: Florida Industrial and Phosphate Research Institute).

(a) The water vapour released during the ammoniation reaction, which accounts for a substantial portion of the water content of the slurry, contains gaseous ammonia, fluorides (such as hydrogen fluoride and silicon tetrafluoride) and ammonium phosphate particles. It is first passed through primary scrubbers that generally use weak phosphoric acid (20–30% P_2O_5) as the scrubbing liquor, principally to recover ammonia and particulates for recycling back to the process. It is then passed through secondary scrubbers that generally use recycled process water to remove fluorides. The effluent from the secondary scrubbers is returned to the process water recycling system.

(b) Exhaust gases from the dryer and cooler, as well as those from product sizing and material transfer operations, also contain ammonia, fluorides and particulates. These streams are treated in the same way as those from the ammoniation reaction, except that they are first passed through cyclones to remove the majority of the particulates.

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TABLE 22. RADIOACTIVITY IN AMMONIUM PHOSPHATE FERTILIZER

Material	Mean activity concentration (Bq/g)					
	U-238	Ra-226	Pb-210	Th-230	Po-210	Th-232
MAP:						
Central Florida, USA [16, 47, 98]	2.0–2.60	0.15–0.20		1.80		0.06
Western USA [98]	1.00	0.03				0.07
Tapira, Brazil [99]	0.61–1.16					0.20–0.22
Catalão, Brazil [99]	1.61–1.85	0.01				0.04–0.07
Brazil [100]	0.26–0.28	0.01–0.02	<0.02–0.04	LLD[a]–0.04		0.23–0.25
Germany [101]	2.00	0.10				
Huelva, Spain [102]	2.96	0.03	—	1.92	0.09	0.026
DAP:						
Central Florida, USA [16, 47]	2.60	0.15				
Northern Florida, USA [47]	0.94	0.02				
Western USA [98]	0.78	0.02				0.003
Huelva, Spain [102]	2.49	0.10		1.54	0.34	0.02
Germany [98]	2.20	0.02				0.02
Brazil [99, 100]	0.37–1.40	<0.005–0.01	<0.02			0.03–0.12
Various NPK fertilizers:						
Germany [50]	0.44	0.27				0.015
Belgium [50]	0.47	0.21				<0.015
Brazil [100]	0.27–0.35	0.42–0.45	0.53–0.64			0.08–0.30
Saudi Arabia [103]	—	0.003–0.28			0.005–0.11	0.002–0.074
Algeria [104]	1.0–1.28	0.13–0.19				0.12–0.13
Romania [105]	0.26	0.26				0.025
Huelva, Spain [102]	0.25–1.24	0.01–0.04		0.19–1.14	0.04–0.29	0.004–0.03

[a] LLD: Lower limit of detection.

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6.2. RADIONUCLIDE ACTIVITY CONCENTRATIONS

The phosphoric acid feedstock contains most of the uranium but very little of the radium originating from the phosphate rock (see Section 5.2). This radionuclide composition is reflected in the dry fertilizer products MAP and DAP [47]. Radionuclide activity concentrations in MAP and DAP dry product and NPK fertilizers are given in Table 22. The reported concentrations of ^{238}U in ammonium phosphate fertilizers produced in different countries generally lie in the range 0.3–3 Bq/g, but in most cases the activity concentration lies in the range 1–2 Bq/g. As expected, the concentration of ^{226}Ra is much lower and is in the range 0.01–0.1 Bq/g. The presence of low levels of ^{232}Th in MAP and DAP is also indicated. Some of the compound fertilizers with different NPK compositions manufactured by mixing with various proportions of potassium salts showed lower activity concentrations of ^{238}U, possibly due to dilution. However, a similar trend is not visible in the case of ^{226}Ra levels.

A comparision of the activity concentration in MAP and DAP bulk product and associated dust particles is given in Table 23. The ^{238}U, ^{226}Ra and ^{210}Pb radioactivity concentrations in bulk product and settled dust from central Florida, USA, are 2.33–4.15 Bq/g, 0.03–0.06 Bq/g and 0.25–0.33 Bq/g, respectively. No significant differences in the concentrations of ^{238}U and ^{226}Ra are found between dry product, settled dust and airborne particles. In the case of ^{210}Pb, however, elevated concentrations (up to 3.2 Bq/g) are found in airborne dust particles, probably due to the attachment of ambient airborne radon decay products.

6.3. OCCUPATIONAL EXPOSURE

6.3.1. Gamma radiation

Doses from external exposure to gamma radiation were assessed at fertilizer plants in central Florida, USA, using individual monitoring with LiF TLDs and Al_2O_3:C OSLDs [53]. The plants produce mainly MAP and DAP, although a small amount of TSP was also produced. The mean annual effective dose was found to be in the range 0.081–0.171 mSv for workers in dry product areas and 0.122–0.197 mSv for workers in shipping and dispatch areas. Investigations have also been carried out at plants in Huelva, Spain, on exposure to gamma radiation and the annual effective dose was found to be in the range 0.076–0.134 mSv [102]. Doses received by workers as a result of external gamma exposure at a fertilizer plant in Poland were assessed using a pressurized ion chamber and LiF TLDs deployed at fixed locations [91]. The mean annual effective dose was found to be 0.10 mSv.

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TABLE 23. ACTIVITY CONCENTRATIONS IN AMMONIUM PHOSPHATE FERTILIZER: COMPARISON OF BULK PRODUCT WITH DUST PARTICLES

Material	Mean activity concentration (Bq/g)		
	U-238	Ra-226	Pb-210
MAP, central Florida, USA:			
Bulk product	2.33	0.06	0.31
Settled dust	2.62	0.04	0.33
Airborne particles ≤100 μm	1.84	0.10	2.31
Airborne particles ≤10 μm	2.04	0.14	3.21
DAP, central Florida, USA:			
Bulk product	3.33	0.04	0.25
Settled dust	4.15	0.03	0.34
Airborne particles ≤100 μm	2.42	0.07	0.60
Airborne particles ≤10 μm	2.57	0.09	0.96
DAP, northern Florida, USA:			
Bulk product	0.94	0.02	
Airborne particles ≤100 μm	1.32	0.04	0.64
Airborne particles ≤10 μm	1.09	0.03	0.94

6.3.2. Inhalation of radionuclides in airborne dust

The inhalation of airborne dust is the predominant exposure pathway [46, 53]. The granulation process generates a considerable amount of dust in the form of crushed dry granulator material, leading to the possibility of this dust being inhaled by workers engaged in activities such as sampling, cleanup of spillage and manual handling. The application of an anti-dust coating to the product reduces the potential for dust generation during subsequent storage and shipping.

Detailed studies on particle size characterization of aerosols and experimental results on lung fluid solubilities have been reported from central Florida phosphate facilities [106–108]. Size measurements indicate that the aerosols do not follow a lognormal distribution and that the particle mass is increasingly concentrated in larger particle sizes in the granulation process locations. It was also noted that the values depend largely on mechanical disturbances by the movement of vehicles and other equipment, ventilation,

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structure of the buildings and operational systems, including granulators, screeners, dryers and conveyors. The samples were collected using a multistage cascade impactor sampler and a high volume sampler at a flow rate of 1130 L/min. The mean airborne dust concentration in the granulation area was 7.2 mg/m^3 and about 55% of the total mass was dominated by large (>20 μm) particles [107].

The lung fluid solubilities of uranium, thorium and lead in fertilizer dust particles (predominantly MAP and DAP) were measured using an in vitro technique involving simulated lung fluid with a neutral pH (7.2–7.4) matching that of the fluid lining the lung. Most of the phosphate, the main constituent of the dust particles, dissolved rapidly in the simulated lung fluid. However, uranium, thorium and lead dissolved less rapidly than the surrounding matrix [109]. The solubilities were found to be relatively independent of the product type or particle size. The most appropriate lung absorption classes determined from these lung solubility measurements were M for uranium and lead and S for thorium, according to the classification of lung absorption types by the ICRP [110]. The lung fluid solubility measurements were supplemented by additional measurements using a simulated lung fluid with an acidic pH (4.5–5.5) to match that of phagolysosomal fluid. The dissolution rate for ^{230}Th under these more acidic conditions was found to be more than 300 times higher than that under neutral conditions. More details on the lung fluid solubility studies reported from the Florida phosphate industry are provided in Annex I.

Annual committed effective doses received by workers from the inhalation of airborne dust in plants in central Florida, USA, were assessed [109] using the ICRP respiratory tract model described in Ref. [37], the particle size measurements reported in Refs [106–108] and the lung solubility measurements reported in Ref. [109]. An annual exposure period of 2000 h was assumed.[18] The results of the assessment are summarized in Table 24.

In phosphate plants in Poland, airborne dust concentrations have been reported as being quite high (3.0–13.5 mg/m^3) [91]. These values were obtained from routine measurements at several locations, including phosphoric acid production and multi-compound fertilizer manufacturing plants. Although these dust concentrations were reported for both phosphoric acid and fertilizer plants, it is likely that they related mostly to fertilizer plants because of the dry nature of the process. Inhalation doses received by workers were assessed from the dust

[18] This annual exposure period is very conservative, since a large portion of the working shift was reported to be spent in the control room or at some other non-dusty location. It has been suggested that a future dose assessment should be based on a more realistic annual exposure period of 500–800 h.

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TABLE 24. DOSES RECEIVED BY WORKERS VIA INHALATION OF AIRBORNE DUST IN AMMONIUM PHOSPHATE PLANTS, FLORIDA, USA [53]

Work site	Mean annual committed effective dose (mSv)	
	Based on solubility in neutral simulated lung fluid	Based on solubility in acidic simulated lung fluid
Granulator area	0.14	0.25
Storage area	0.10	0.16
Shipping area	0.03	0.05

concentrations, assuming an AMAD of 1 μm. The radionuclide activity concentrations in the dust were not measured, but were, instead, estimated from the values measured for raw materials and fertilizers in the workplace. The assessed doses were in the range 2.9–5.6 mSv/a. It was reported that the lack of sufficient data for sensitive inhalation dose parameters had necessitated the application of conservative assumptions and probably resulted in the doses being overestimated.

6.3.3. Inhalation of radon

Radon concentration measurements have been made in plants in Huelva, Spain [94], and Florida, USA [53]. In all cases, the radon concentrations were at normal background levels. Consequently, inhalation of radon by workers is not regarded as a significant exposure pathway.

6.3.4. Total effective dose

The total annual doses received by workers in ammonium phosphate fertilizer plants can be estimated by summing the gamma doses reported in Section 6.3.1 and the dust inhalation doses given in Table 24. The results are given in Table 25 and show that a worker receives, at most, a dose of a few tenths of a millisievert per year.

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TABLE 25. TOTAL DOSES RECEIVED BY WORKERS IN AMMONIUM PHOSPHATE FERTILIZER PLANTS, FLORIDA, USA

Work site	Total annual committed effective dose (mSv)	
	Minimum	Maximum
Dry product areas	0.22	0.42
Storage areas	0.22	0.36
Shipping areas	0.15	0.25

6.4. PUBLIC EXPOSURE

6.4.1. Fertilizer production

Public exposure may arise as a result of airborne dust emissions, disposal of spillages of solid material, storm water runoff contaminated by spillages and other inadvertent discharges caused by operating factors. These can be minimized by good housekeeping procedures, including, in particular, the prompt cleanup of spillages of process material. Control of spillage also brings economic benefit by retaining valuable product material. Provided that such measures are adopted, exposure of members of the public is likely to be insignificant.

6.4.2. Fertilizer use

As the use of fertilizer is subject to the requirements for existing exposure situations (see Ref. [2] and Section 3.1.1), agricultural workers exposed to phosphate fertilizer should be treated as members of the public. Exposures may vary widely from place to place depending upon the application rate of fertilizers and local environmental conditions. In an investigation carried out in Germany, the average dose received during the application of fertilizer was 0.6 μSv/a and the maximum likely dose was 4 μSv/a [59]. An investigation was also carried out in South Africa on the use of fertilizers produced from igneous phosphate rock [111]. A detailed assessment of the doses received by agricultural workers, considering all pathways of exposure, found that the doses never exceeded 10 μSv/a, based on conservative assumptions, including worst case scenarios. Evidence suggests that public exposure attributable to the use of ammonium phosphate fertilizers is of no significant concern.

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6.5. REGULATORY CONSIDERATIONS

The activity concentrations of radionuclides such as ^{238}U in both the phosphoric acid feedstock and the fertilizer product generally exceed 1 Bq/g. In terms of the Standards, therefore, the production of ammonium phosphate fertilizer needs to be considered for regulation as a practice. However, the evidence suggests that annual doses received by workers are consistently below 1 mSv and that there are no significant exposure pathways to members of the public. The most appropriate regulatory option for fertilizer production activities would seem to be either the granting of an exemption or a requirement for notification. This would be especially appropriate in situations where, as part of good industrial practice, basic OHS and environmental protection measures are in place, including measures for the management of process water, the containment of spillages and the control of airborne dust and discharges to the environment. The use of ammonium phosphate fertilizer does not need to be subject to any restrictions in terms of the requirements for existing exposure situations.

The radionuclide activity concentrations in the process materials and products are such that the transport of these materials would not fall within the scope of application of the Transport Regulations.

7. MANUFACTURE AND USE OF SUPERPHOSPHATE FERTILIZERS

Superphosphates represent a class of fertilizer product made by direct but partial acidulation of phosphate rock to render the phosphate mineral content largely water soluble. Various forms of insoluble apatite, which consist essentially of tricalcium phosphate, are converted to MCP using either sulphuric acid or phosphoric acid.

7.1. PROCESS DESCRIPTION

7.1.1. Single superphosphate (SSP)

SSP (known also as 'normal', 'simple' or 'ordinary' superphosphate) is a mixture of (water soluble) MCP and $CaSO_4$, with a P_2O_5 content of 16–22%. It is manufactured by reacting phosphate rock, usually a fluorapatite, with sulphuric acid. The basic chemical reaction is:

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$$Ca_{10}(PO_4)_6F_2 + 7H_2SO_4 \rightarrow 3Ca(H_2PO_4)_2 + 7CaSO_4 + 2HF$$

In contrast with the use of sulphuric acid digestion to produce phosphoric acid (see Section 5.1.1), the $CaSO_4$ produced by the digestion process is not separated out but, instead, remains as a component of the final product. There are many side reactions involving fluorine compounds, the most significant being:

$$4HF + SiO_2 \rightarrow SiF_4 + 2H_2O,$$

$$3SiF_4 + 4H_2O \rightarrow SiO_2 \cdot 2H_2O + 2H_2SiF_6$$

and

$$SiF_4 + 2HF \rightarrow H_2SiF_6$$

The production process is, in principle, very simple and dates back to the 19th century. In modern SSP plants, the phosphate rock is processed by one of two methods:

(i) The rock is dry milled to a particle size of 90–95% <150 μm and then reacted with 70–75% strength sulphuric acid in a high speed mixer; or
(ii) The rock is wet milled and the resulting slurry is reacted with 98% strength sulphuric acid, the water content of the slurry causing the acid to be diluted within the mixer.

To facilitate completion of the reaction, a slight excess of sulphuric acid is used. The exothermic nature of the reaction raises the temperature to more than 90°C. From the mixer the slurry is sent to a 'den' where it solidifies on a travelling grate or rubber belt. The solid SSP is excavated 30 min to 4 h later, the exact period depending on the temperature, the reactivity of the rock and the degree of excess acid used. The excavated material is then processed in one of two ways to produce a final product that is uniform in composition and size:

(i) The material is conveyed to a storage building (adequately ventilated to prevent the buildup of fluoride vapours), where the reaction continues for 2–6 weeks in a process called 'curing', after which the hardened and cured product is milled and screened before shipment as 'powder SSP'; or
(ii) The material is converted into a granular form using water and steam and then screened to separate out granules of the required size; oversize granules are milled and, together with the undersize granules, returned to the granulation step.

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Most modern plants are completely mechanized. A typical production unit requires as few as two or three operators. Plants are generally regulated with regard to HF and SiF_4 emissions. By means of a water scrubber, HF generated by the acid digestion reaction and sometimes also fluoride vapours released within storage buildings are captured and returned with the scrubber water to the process water recycling system.

7.1.2. TSP

TSP consists entirely of MCP, with an available P_2O_5 content of 43–48%. It is produced by reacting phosphate rock (fluorapatite) with phosphoric acid (and sometimes sulphuric acid) and is manufactured in two basic product forms, the first being known as non-granular or 'run-of-pile' TSP (ROP-TSP) and the second as granular TSP (GTSP). The larger, more uniform particle size of GTSP gives it improved storage and handling characteristics. The basic chemical reaction is:

$$Ca_{10}(PO_4)_6F_2 + 12H_3PO_4 + 9H_2O \rightarrow 9Ca(H_2PO_4)_2 \cdot H_2O + CaF_2$$

Side reactions involving fluorine compounds include:

$$2CaF_2 + 4H_3PO_4 + SiO_2 \rightarrow SiF_4 + 2Ca(H_2PO_4)_2 + 2H_2O$$

and

$$3SiF_4 + 4H_2O \rightarrow SiO_2 \cdot 2H_2O + 2H_2SiF_6$$

The manufacturing process for ROP-TSP is similar to that for SSP (see Section 7.1.1). Phosphate rock and concentrated phosphoric acid (50–54% P_2O_5) are brought together in a cone or other high speed mixer, which discharges directly into a continuously moving 'den'. A very dense slurry is produced, which, after solidifying into a porous, honeycomb-like mass, is pulverized by a rotary cutter into particles of various sizes. The particles are conveyed to the storage area for pile curing where the reaction continues for 3–5 weeks. The cured material is excavated and shipped as ROP-TSP or is converted into GTSP by treatment with water and steam in a granulator, followed by drying and screening.

GTSP is also manufactured directly by reacting milled phosphate rock with lower strength phosphoric acid (32–40% P_2O_5). The lower acid concentration allows the reaction products to be maintained in a fluid state throughout the mixing period of 1–2 h. The resulting slurry is mixed with a large amount of

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dried, fine granules that have been recycled back from the product screening step. These granules become enlarged as a result of coating with the slurry. The coated granules are dried in a rotary dryer, with the heat of the dryer causing the chemical reaction to be accelerated towards completion. The dried granules are then sized using vibrating screens. Product size granules separated out by the screens are cooled in a countercurrent rotary drum or fluidized bed air cooler and then sent to a storage pile for curing. After a minimum curing period of 3–5 d, the granules are ready for bagging and shipping. Granules not meeting the size specifications are recycled back to the process (after crushing, in the case of oversize granules).

Residues accumulate in the processing equipment over time. These are removed periodically, typically every 2–4 weeks, and are sent to the process water recycling system.

Airborne particles are generated during the unloading, grinding, storage and transfer of ground phosphate rock and are controlled by air extraction systems and baghouse collectors. The baghouse cloth filters are reported to have removal efficiencies of over 99%. The collected particles are recycled back to the process. Gaseous fluorides (SiF_4 and HF) and airborne particles are generated by the acidulation reaction, although fluoride emanation from the storage pile in the curing building is relatively small because the acidulation reaction is, at that stage, almost complete. Airborne particles are also generated by the dryer, screens, cooler, mills and transfer conveyors. Emissions of fluorides and particles from the production area and curing building are controlled by scrubbing the off-gases with recycled pond water in cyclonic scrubbers. Emissions from the dryer, cooler, screens, mills, product transfer systems and product storage building are sent to a cyclone separator for removal of a portion of the dust before going to wet scrubbers to remove fluorides. Tail gas wet scrubbers perform final cleanup of the plant off-gases. The efficiencies of fluoride control are 90–99%, while an efficiency of 98% is achievable for particulate control. Used scrubber water is normally sent to the process water recycling system.

7.2. RADIONUCLIDE ACTIVITY CONCENTRATIONS

The reaction of phosphate rock with either sulphuric acid or phosphoric acid leading directly to a fertilizer product does not cause any of the radioactive material to precipitate selectively or concentrate in any manner. The radionuclide content of the fertilizer product reflects the combined radionuclide content of the phosphate rock and, where used, phosphoric acid [47]. Consequently, the activity concentrations of ^{238}U series radionuclides in SSP are all about 1 Bq/g, approximately 30% lower than those in the phosphate rock owing to the mass

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increase from the addition of sulphuric acid. The ^{238}U activity concentration in GTSP is typically about 2.5 Bq/g, some 70% higher than that in the phosphate rock as a result of the addition of uranium via the phosphoric acid, while the ^{226}Ra activity concentration is about 1 Bq/g, approximately 40% lower than that in the phosphate rock. Given that the radionuclide activity concentrations in the phosphate rock and, where used, phosphoric acid are themselves quite moderate, the consequences of radionuclide dilution (SSP) or concentration (^{238}U in GTSP) are, for most rock sources, not of any great significance. Actual activity concentration data reported for several countries are given in Table 26.

7.3. OCCUPATIONAL EXPOSURE

Occupational exposures were investigated in four plants in Poland producing SSP, TSP and NPK fertilizers [91]. Doses from external exposure to gamma radiation were assessed using a pressurized ion chamber and LiF TLDs deployed at fixed locations. The mean annual effective dose from gamma radiation was found to be 0.05 mSv for the SSP plant and 0.20 mSv for the TSP plant.

TABLE 26. RADIONUCLIDE ACTIVITY CONCENTRATIONS IN SUPERPHOSPHATE FERTILIZERS

Material	Mean activity concentration (Bq/g)		
	U-238	Ra-226	Pb-210
SSP:			
Florida, USA [50]	0.74	0.79	
Belgium [50]	1.10	0.91	
Germany [50]	0.52	0.52	
Former USSR [50]		0.11	0.30
Poland [91]	0.78	0.91	—
Brazil [100]	0.41	0.87	1.25
TSP:			
Central Florida, USA [47, 50]	2.10	0.78	
Northern Florida, USA [50]	0.96	0.43	
Western states, USA [50]	1.60	0.52	
Germany [50]	0.80	0.23	
Poland [91]	1.79	0.86	
Brazil [100]	0.22	0.12	0.20

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Inhalation dose assessments were carried out in phosphate fertilizer plants in Florida, USA [53]. Using various assumptions, the average annual committed effective dose from dust inhalation was conservatively estimated to be <0.05 mSv in the dry product areas and <0.8 mSv in the shipping and storage areas. These inhalation doses, although conservative, could be regarded as being reasonably representative of those received in SSP and TSP plants. Follow-up studies, aimed at removing the need for some of the conservative assumptions, indicated that the inhalation doses were likely to be lower, and well below 1 mSv/a [112].

7.4. PUBLIC EXPOSURE

7.4.1. Fertilizer production

During the fertilizer production process, it is evident that airborne emissions of fluorides and particulate matter are controlled very effectively. In addition, the small amounts of solid residues generated in these emission control systems and elsewhere are managed as part of the process water recycling system. It can be concluded that these pollution control measures will also be effective in controlling the release of radionuclides to the environment. Given that there are no other obvious exposure pathways to the public during the manufacturing process, it can be concluded that public exposure attributable to superphosphate fertilizer production is of no significant concern.

7.4.2. Fertilizer use

There is a potential for exposure of agricultural workers (who, in terms of the requirements for existing exposure situations [2], are regarded as members of the public) as a result of the use of superphosphate fertilizers. However, the lower activity concentrations in supherphosphate fertilizers compared with those in ammonium phosphate fertilizers (see Section 6) suggest that the doses are likely to be insignificant.

7.5. REGULATORY CONSIDERATIONS

The activity concentrations of radionuclides such as ^{238}U in the phosphoric acid feedstock and in the GTSP fertilizer product generally exceed 1 Bq/g. In terms of the Standards, therefore, the production and use of superphosphate fertilizer needs to be considered for regulation as a practice. However, the annual doses received by workers are consistently below 1 mSv and there are no

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significant exposure pathways to members of the public. The most appropriate regulatory option for superphosphate fertilizer production activities would seem to be either the granting of an exemption or a requirement for notification. This would be especially appropriate in situations where, as part of good industrial practice, basic OHS and environmental protection measures are in place, including measures for the management of process water, the containment of spillages and the control of airborne dust and discharges to the environment. The use of superphosphate fertilizer would not need to be subject to any restrictions in terms of the requirements for existing exposure situations.

The radionuclide activity concentrations in the process materials and products are such that the transport of these materials would not fall within the scope of application of the Transport Regulations.

8. MANUFACTURE AND USE OF NITROPHOSPHATE FERTILIZERS (NITRIC ACID DIGESTION)

8.1. PROCESS DESCRIPTION

The treatment of phosphate rock with nitric acid using a process known as the 'ODDA process' produces phosphate fertilizer and calcium nitrate, which is also a fertilizer. The properties of the fertilizer products are such that they may not be as broadly competitive as other fertilizers, but their specialized nature has made them the subject of growing interest. Plants using this technology have operated in Finland, Germany, Italy, Netherlands, Norway, Romania and Sweden [113, 114]. Some plants in Pakistan also use this technology to produce nitrophosphate fertilizer [115].

The main reaction between nitric acid and phosphate rock is as follows:

$$Ca_{10}(PO_4)_6F_2 + 20HNO_3 \rightarrow 6H_3PO_4 + 10Ca(NO_3)_2 + 2HF$$

After the separation of the insoluble material, phosphoric acid is neutralized with ammonia to produce a fertilizer. If the calcium nitrate is left in the solution, it reverts to dicalcium phosphate upon ammoniation as per the following reaction:

$$2H_3PO_4 + Ca(NO_3)_2 + 4NH_3 \rightarrow CaHPO_4 + (NH_4)_2HPO_4 + 2NH_4NO_3$$

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On heating the paste-like mixture to drive off the free moisture, the water solubility of the phosphate in the dried residue is greatly reduced due to the formation of dicalcium phosphate, as described by the following equation:

$$Ca(H_2PO_4)_2 + 2Ca(NO_3)_2 \rightarrow 2CaHPO_4 + Ca(NO_3)_2 + 2HNO_3$$

The nitric acid evolved during this step corresponds to approximately 25% of the nitric acid originally added. The dried product contains phosphate and nitrogen but the phosphate is of low solubility. The calcium nitrate content is sufficient to give the material undesirable hygroscopic properties and the sticky, pasty product is not well suited for shipment or for spreading as a dry bulk fertilizer [116, 117]. The properties can be improved by deep cooling the mixture and precipitating some of the calcium nitrate.

A more acceptable product is obtained if the mixture of phosphoric acid, calcium phosphate and calcium nitrate, with or without the partial removal of calcium nitrate, is treated with ammonia, although ammoniation causes the calcium to form a citrate soluble calcium phosphate [113] rather than the water soluble phosphates that are present in MAP or DAP (see Section 6). Dicalcium phosphate is usually insoluble in water but soluble in ammonium citrate solution and is, therefore, regarded as a source of 'available' P_2O_5. However, fertilizer specification often requires water solubility and this type of product is limited to 50% water solubility of the P_2O_5. The calcium can also be removed by precipitation with sulphate, the sulphate being added as sulphuric acid or ammonium sulphate [118], leaving only the phosphoric acid component of the mixture. The reaction with sulphuric acid produces nitric acid and phosphogypsum (calcium sulphate), according to the following reaction:

$$Ca(NO_3)_2 + H_2SO_4 \rightarrow 2HNO_3 + 2CaSO_4$$

The nitric acid produced by the reaction may be recovered and recycled back to the process. However, as a means of producing phosphoric acid, the nitric acid process has no significant advantage over the more usual process involving the digestion of the phosphate rock with sulphuric acid.

A variety of fertilizers is produced from the addition of compounds such as calcium carbonate (lime), carbon dioxide, ammonia, potassium chloride or potassium sulphate. These include calcium ammonium nitrate, granular ammonium nitrate, granular ammonium sulphate with added potassium and various granular NPK products. A simplified diagram of the various process steps employed to produce ammonium nitrate fertilizers (calcium ammonium nitrate and NPK) is given in Fig. 27.

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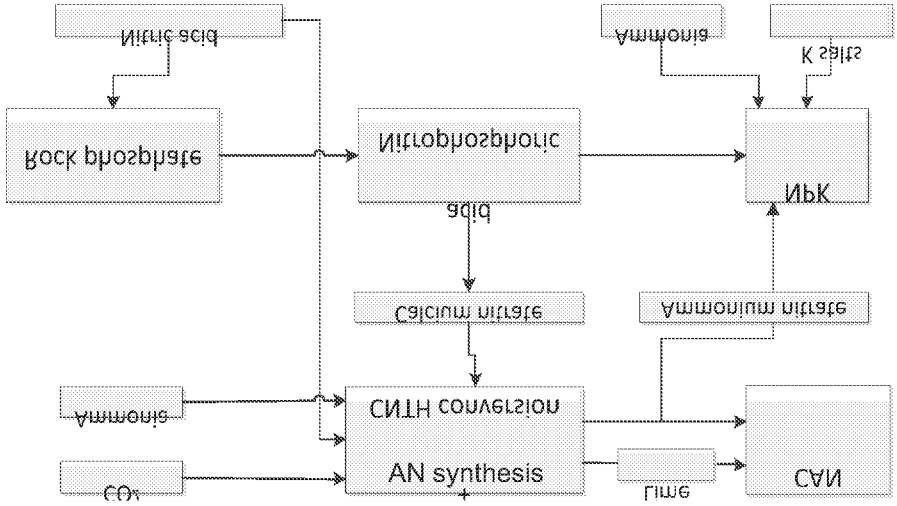

FIG. 27. Nitric acid route to nitrophosphate fertilizer production (CNTH: calcium nitrate tetrahydrate; AN: ammonium nitrate; CAN: calcium ammonium nitrate fertilizer; NPK: nitrogen–phosphorus–potassium fertilizer) [117].

The nitric acid processing route generates gaseous emissions of NO_x, NH_3 and HF to the atmosphere, as well as small amounts of silica (sand). Depending on radionuclide activity concentrations, the sand may be used for construction purposes.

8.2. RADIONUCLIDE ACTIVITY CONCENTRATIONS

All the radioactivity in the phosphate rock feedstock ends up in the fertilizer products, although at lower activity concentrations because of dilution due to the addition of nitric acid, ammonia and other compounds. The precipitation of calcium nitrate, where practised, does not affect this situation because the radioactivity remains with the phosphoric acid during the precipitation step. Should the calcium be precipitated by the addition of sulphuric acid, the phosphogypsum so produced would contain most of the radium but very little of the uranium. The actual activity concentrations reported from a few countries where nitrophosphate fertilizers have been produced are given in Table 27. The reported ^{238}U activity concentrations are in a narrow range and typically about 0.4 Bq/g. One of the plants in Belgium produced nitrophosphate fertilizers for more than three decades and the typical radium activity concentration in the fertilizers never exceeded 0.1 Bq/g [95].

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TABLE 27. RADIONUCLIDE ACTIVITY CONCENTRATIONS IN NITROPHOSPHATE FERTILIZERS

Country	Mean activity concentration (Bq/g)		
	U-238	Ra-226	Pb-210
Italy [114]	0.37	0.12	0.21
Belgium [95]		0.10	
Germany [50]	0.40	0.30	
Romania [105]	0.26–0.36	0.26–0.36	
Pakistan [115]		0.39	

8.3. OCCUPATIONAL EXPOSURE

Gamma dose rates have been measured in production areas and raw material and end product warehouses in a nitrophosphate fertilizer plant in Italy [119]. The dose rates in the production areas were 0.15–0.2 μSv/h, comparable with background levels. Slightly elevated dose rates in the range 0.12–1.10 μSv/h were measured in the end product storage areas and were mainly due to the high percentage of ^{40}K present in the products. Data were also reported from the plant on the mass concentrations of airborne dust at several locations in the production areas and storage areas. The mean dust levels were in the range 0.1–2.1 mg/m^3 in the hoppers, reactors, granulation and other areas of the production unit. Higher levels of dust were found in the raw material warehouse and fertilizer product storage areas, where the mean concentrations were 5.4 and 1.7 mg/m^3, respectively.

The annual effective doses received by workers from gamma radiation and inhalation of airborne dust reported in Ref. [119] are summarized in Table 28. These estimates are based on a conservative assumption of the periods spent by the workers in various work locations and probably reflect an upper estimate. Summing of the doses from external gamma exposure and inhalation of airborne dust gives total annual effective doses in the range 0.3–0.7 mSv.

Radon concentrations were also reported from the plant. Measurements showed radon concentrations to be in the range 40–60 Bq/m^3 in production areas, comparable with the natural background concentration at the site. However, elevated levels, up to 210 Bq/m^3, were found in the raw material and end product warehouse, especially during the winter season.

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TABLE 28. ESTIMATED DOSES RECEIVED BY WORKERS IN A NITROPHOSPHATE PLANT [119]

Work site	Mean annual effective dose (mSv)			
	Gamma radiation	Dust inhalation	Dust ingestion	Total
Raw material storage areas	0.4	0.04	0.006	0.45
Production area	0.3	0.03	0.01	0.34
Fertilizer product bagging	0.4	0.3	0.013	0.71
Pallet control	0.4	0.12	0.013	0.53
Product storage areas	0.6	0.13	0.013	0.74
Product bagging and warehouses	0.3	0.12	0.013	0.43

8.4. PUBLIC EXPOSURE

8.4.1. Fertilizer production

Using conservative assumptions, the maximum annual effective dose received by individuals living near a nitrophosphate fertilizer manufacturing plant in Italy was assessed [119]. The maximum annual inhalation dose from airborne dust was about 4 μSv, based on the predicted ground level air concentration at a distance of 0.2 km from the plant. The contribution of external gamma exposure was negligible at the site.

8.4.2. Fertilizer use

From the radionuclide activity concentrations reported in Table 27, it can be concluded that the exposure of agricultural workers (who, in terms of the requirements for existing exposure situations [2], are regarded as members of the public) as a result of the use of nitrophosphate fertilizers is of no significant concern.

8.5. REGULATORY CONSIDERATIONS

The activity concentrations of radionuclides such as ^{238}U in the phosphoric acid feedstock generally exceed 1 Bq/g, whereas in the nitrophosphate fertilizer

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product, the activity concentration is below 1 Bq/g. In terms of the Standards, therefore, the production of nitrophosphate fertilizer needs to be considered for regulation as a practice. However, the evidence suggests that annual doses received by workers are consistently below 1 mSv and that there are no significant exposure pathways to members of the public. The most appropriate regulatory option for fertilizer production activities would seem to be either the granting of an exemption or a requirement for notification. This would be especially appropriate in situations where, as part of good industrial practice, basic OHS and environmental protection measures are in place, including measures for the management of process water, the containment of spillages and the control of airborne dust and discharges to the environment. The use of nitrophosphate fertilizer does not need to be subject to any restrictions in terms of the requirements for existing exposure situations.

The radionuclide activity concentrations in the process materials and products are such that the transport of these materials would not fall within the scope of application of the Transport Regulations.

9. MANUFACTURE AND USE OF ANIMAL FEED PHOSPHATES

The phosphate industry produces animal feed additives that contain various mixtures of phosphates and other nutrients, especially nitrogen, as well as micronutrients such as magnesium, sulphur and zinc. The phosphate content consists mainly of calcium phosphate in one form or another, with calcium being particularly effective as an animal feed supplement when used in conjunction with phosphorus. Since phosphate ores contain fluorine, which is toxic to animals, it is necessary to ensure that the fluorine content of the product is very low (less than 1% of the phosphorus content). Two basic types of animal feed phosphate are produced:

(i) The first type contains tricalcium phosphate and is therefore marketed under the name TCP. It is also known as defluorinated phosphate rock. TCP is relatively high in calcium and derives its phosphorus content from a mixture of phosphate rock concentrate and phosphoric acid. It contains a minimum of 30% calcium and 18% phosphorus and can be represented by the chemical formula $Ca_3(PO_4)_2 \cdot Na_3PO_4 \cdot Ca_2SiO_4$.

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(ii) The second type, the more popular of the two, contains MCP, dicalcium phosphate or mixtures of the two in various proportions. The products are marketed as a range of products referred to generically as MCP–DCP or 'granular DCP', or more specifically as MCP or DCP. These products are lower in calcium than TCP and derive their phosphorus content only from phosphoric acid or phosphate rock, depending on the production process used. Products marketed as MCP contain 15–20% calcium and 21% phosphorus, while products marketed as DCP contain 18–24% calcium and 18.5% phosphorus. MCP is also marketed as a fertilizer.

9.1. PROCESS DESCRIPTION

9.1.1. TCP animal feed

TCP is manufactured by mixing phosphate rock with phosphoric acid and sodium hydroxide and calcining the mixture at a temperature of 1370–1510°C. These conditions cause the fluorine in the feedstock materials to be driven off in the form of gaseous HF and convert the phosphate mineral into a biologically available form. Depending on the type of calciner used, steam may need to be added to facilitate the defluorination reaction. After cooling, the calcined material is granulated, dried and screened to produce TCP granules of the required size.

9.1.2. MCP–DCP animal feed

9.1.2.1. Reaction of phosphoric acid with limestone

Most MCP–DCP animal feed phosphates are produced by reacting defluorinated phosphoric acid (38–42% P_2O_5) with high quality finely ground limestone. Typically, the limestone contains 93–97% $CaCO_3$ and its particle size distribution is such that about 90% passes through a 200 Tyler mesh screen (0.075 mm). The neutralization of phosphoric acid with limestone can produce five different forms of calcium phosphate: $Ca(H_2PO_4)_2$; $Ca(H_2PO_4)_2 \cdot H_2O$; $CaHPO_4$; $CaHPO_4 \cdot 2H_2O$; and a crystalline product of variable composition having the X ray diffraction pattern of an apatite in which $Ca_3(PO_4)_2$ has been arbitrarily singled out from the hydroxyapatite family. The reactions with the limestone are as follows:

$$2H_3PO_4 + CaCO_3 \rightarrow Ca(H_2PO_4)_2 \cdot H_2O + CO_2$$

$$Ca(H_2PO_4)_2 + CaCO_3 \rightarrow 2CaHPO_4 + CO_2 + H_2O$$

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$$H_3PO_4 + CaCO_3 \rightarrow CaHPO_4 + CO_2 + H_2O$$

$$H_3PO_4 + CaCO_3 + H_2O \rightarrow CaHPO_4 \cdot 2H_2O + CO_2$$

There is some evidence that, at moderate temperatures, the first solid to appear is dicalcium phosphate dihydrate. This hydrolyses readily to MCP monohydrate and tricalcium phosphate (apatite), according to the reaction:

$$4CaHPO_4 \cdot 2H_2O \leftrightarrow Ca(H_2PO_4)_2 \cdot H_2O + Ca_3(PO_4)_2 + 8H_2O$$

In the presence of water, MCP monohydrate hydrolyses to give dicalcium phosphate and phosphoric acid, according to the reaction:

$$Ca(H_2PO_4)_2 \cdot H_2O \leftrightarrow CaHPO_4 + H_3PO_4 + H_2O$$

The reaction between the phosphoric acid and limestone is carried out in a high speed mixer followed by a granulator and is allowed to proceed nearly to completion in order to release as much carbon dioxide as possible. Material from the granulator is dried and then conveyed to sizing screens where it is separated into a product size fraction, an oversize fraction and fines. The oversize fraction is ground and, together with the fines from the screens and from the dust collection systems on the dryer, cooler and other equipment, is recycled to the granulator to provide seed nuclei for the granulation process. The on-size product from the screen is cooled and sent to storage.

A new method of producing dicalcium phosphate placed product on the market for the first time in 2009. The new method uses a previously unexploited part of the existing wet-acid process [120]. The conventional pre-release process for treating acidic water in phosphogypsum stacks by neutralizing the water using lime is not effective in removing phosphates. In the new treatment process, the phosphate content is recovered and used for producing dicalcium phosphate.

9.1.2.2. Reaction of phosphate rock with hydrochloric acid

MCP and DCP may also be produced by the acidulation of phosphate rock with hydrochloric acid. The reaction generates residues in the form of HF gas and a liquid effluent charged with $CaCl_2$. For the production of MCP, the reaction proceeds as follows:

$$Ca_{10}F_2(PO_4)_6 + 14HCl + 3H_2O \rightarrow 3Ca(H_2PO_4)_2 \cdot H_2O + 7CaCl_2 + 2HF$$

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Excess calcium salts react with the liberated HF, resulting in the precipitation of insoluble CaF_2. The effluent is discharged to surface water bodies after treatment. About 0.5 t of solid waste is produced per tonne of P_2O_5. It is reported that this solid waste is deposited in stacks [85], as is the case with phosphogypsum.

For the production of DCP, phosphate rock is digested with hydrochloric acid repeatedly followed by decanting at each digestion step. The digested fraction of the phosphate rock is further treated with high quality limestone to precipitate the P_2O_5 from the solution. The white pulp generated is washed and vacuum filtered and the solid fraction is allowed to proceed to a drier to become DCP product. The liquid fraction, predominantly $CaCl_2$ effluent resulting from the filtration of the white pulp is released to a two or three step decantation and settling process and finally the residual water is treated in a water treatment facility before discharge. The undigested solid fraction is filtered and disposed of along with the water treatment sludge generated in the subsequent process steps. The liquid effluent obtained during the filtration of the sludge is usually sent to the water treatment facility where the effluent is treated along with the residual water from the DCP production line [25, 121].

9.2. RADIONUCLIDE ACTIVITY CONCENTRATIONS

It is reported in Ref. [25] that TCP contains ^{210}Pb and ^{210}Po each at an activity concentration of 0.1 Bq/g. In the case of MCP and DCP, the radionuclide compositions depend on whether production is by reacting phosphoric acid with limestone or by reacting phosphate rock with hydrochloric acid.[19] Data on radionuclide activity concentrations in MCP and DCP are given in Table 29. With regard to the phosphoric acid route, the new DCP production method described in Ref. [120] reduces the ^{238}U and ^{226}Ra concentrations in the DCP product to only 10% of the levels found in DCP produced by the more traditional method.

In the production of DCP by the hydrochloric acid route, there is an inhomogenous distribution of uranium series radionuclides between the different process outputs. The radionuclides ^{238}U and ^{210}Pb dominate in the DCP product whereas ^{230}Th and ^{210}Po dominate in the solid wastes. Although the activity concentration of ^{210}Po in the DCP is initially lower in comparison with ^{210}Pb, this

[19] The heavy metals content is also affected — the phosphoric acid route generally produces relatively high concentrations of Cd and other metals such as Mg, Al, Fe and Cr in the final DCP product, whereas the hydrochloric acid route leads to relatively high Pb and As concentrations.

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TABLE 29. RADIOACTIVITY IN ANIMAL FEED PHOSPHATES

Material	Activity concentration (Bq/g)									Reference	Additional information
	U-238	Th-230	Ra-226	Bi-214	Pb-210	Po-210	Th-232	Ra-228	Th-228		
Phosphoric acid + limestone process route:											
MCP	0.11 (0.04–0.165)		<0.17		0.13		0.23 (0.07–0.426)	<0.27	0.179	[48]	Igneous feedstock, South Africa
DCP		1	<0.03		<0.03	<0.03				[25]	Sedimentary feedstock, Morocco
DCP	0.67		0.50	0.01	0.01					[120]	Sedimentary feedstock, central Florida, USA
DCP	0.06		0.05							[120]	Sedimentary feedstock, new production method
Hydrochloric acid + phosphate rock process route:											
MCP	1.57		0.014							[85]	'Monocal-TCH'
MCP–DCP	2.47		0.010							[85]	'Modical-TCI'
DCP	1.21		0.018							[85]	'DCP-TCH'
DCP	2.06		0.016							[85]	'Dical-TCI'
DCP	2.30		0.010							[85]	'Dical-TCR'
DCP	0.95	0.01	0.015[a]		0.17	0.35				[122]	Feedstock: 0.838 Bq/g U-238
DCP	1.5–1.7	0.1–0.4	0.1–0.2		2.0–2.1	0.1–0.8				[25,121]	Sedimentary feedstock, Morocco

[a] It is reported that most of the Ra-226 migrates to the calcium chloride.

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radionuclide grows back into equilibrium with ^{210}Pb after a relatively short time. The process generates two liquid effluents together with a sludge which is mainly the water treatment sludge [25]. The radionuclide activity concentrations in these process residues are given in Table 30. Radium, being chemically similar to calcium, forms $RaCl_2$ together with the $CaCl_2$. The addition of $BaCl_2$ to the $CaCl_2$ effluent during the effluent treatment process will cause about 90% of the radium to precipitate as radium sulphate, which, together with $BaSO_4$, will end up as part of the solid waste. The ^{226}Ra activity concentration in the solid waste is reported to be in the range 2–10 Bq/g [85]. If the effluent is not treated with $BaCl_2$, the $RaCl_2$ will remain in solution during the effluent treatment process and will be discharged to surface water bodies along with the treated process water.

9.3. OCCUPATIONAL EXPOSURE

Most modern production facilities have a high degree of automation that makes it unnecessary for workers to spend much time in production areas. Gamma dose rates measured in a DCP production plant gave incremental dose rates in the range 0.1–0.2 μSv/h across different production locations. Annual effective doses received by workers through the gamma exposure pathway were estimated to be approximately 0.1 mSv [122]. Dust measurements were also reported from the plant. The main source of dust was identified as the product drying operation. Occasionally, dust was released from the containers feeding phosphate rock into the process tanks. The average dust concentration in the DCP production area was 3.5 mg/m^3 and the inhalation dose received by workers in that area was 0.07 mSv/a. It was concluded that dust could be a hazard in DCP manufacturing plants and that dust control measures and restrictions on periods of exposure to dust were important in reducing inhalation doses. Studies were also carried out to assess indoor radon in a DCP plant. No significant increase above the background levels was observed. For all exposure pathways, the annual effective doses received by workers were found to be much less than 1 mSv.

TABLE 30. RADIOACTIVITY IN RESIDUES FROM THE PRODUCTION OF DCP BY HYDROCHLORIC ACID DIGESTION OF PHOSPHATE ROCK [25]

Residue	Activity concentration (Bq/L)				
	U-238	Th-230	Ra-226	Pb-210	Po-210
Residual water			44–55		0.0061
Liquid effluent			9.1–20	0.006	0.008–0.04
Sludge	5.0–5.3	10.1–11.9	0.66–2.3	0.66–1.2	7.9–13

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9.4. PUBLIC EXPOSURE

9.4.1. Animal feed production

Measurements of gamma dose rates and radon concentrations have been reported for four stack deposits containing solid waste associated with the production of MCP by hydrochloric acid digestion [85]. The results are given in Table 31. Assuming that the measurements were made close to the stacks (the distance is not specified), it is unlikely that any significant dose would be received by a member of the public living at a reasonable distance from the stacks. The results suggest quite strongly that, for the four stacks investigated, capping had no significant effect on radon exhalation. It is difficult to determine from the results whether capping had any significant influence on gamma radiation.

In a typical phosphoric acid and fertilizer production facility, any DCP production via the phosphoric acid route is generally a small part of the total production. As a consequence, the disposal of solid waste from DCP production into the phosphogypsum stack will have negligible impact on its radiological characteristics. A detailed study was performed to assess the radiological impact on the public arising from the disposal of solid waste from DCP production over a period of more than a decade [123]. The potential for remobilization of the radionuclides and their migration into freshwater systems, surface soils, fish, fruit and vegetables was examined and no enhancement in uranium series radionuclide concentrations was observed. The annual effective dose to the public from ^{210}Pb and ^{210}Po through the ingestion of food was estimated to be 0.03 mSv, which is comparable with the background levels in the region.

TABLE 31. EXPOSURE LEVELS AT WASTE STACKS ASSOCIATED WITH THE PRODUCTION OF MCP BY DIGESTION OF PHOSPHATE ROCK WITH HYDROCHLORIC ACID [85]

Stack volume (million m^3)	Ra-226 activity concentration (Bq/g)	Capping	Exposure level		Mean exposure level per unit Ra-226 concentration	
			Gamma dose rate (μSv/h)	Radon concentration (Bq/m^3)	Gamma dose rate (μSv/h)	Radon concentration (Bq/m^3)
0.1	3–4	No	1	60	0.3	17
0.5	3–4	Yes	1	30–85	0.3	16
0.1	2–4	Yes	0.05–0.25	30–80	0.1	18
1.4	3.5–10	No	2.6	50–200	0.4	19

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9.4.2. Animal feed consumption

The use of animal feed containing radionuclides of natural origin is subject to the requirements for existing exposure situations [2]. In terms of these requirements, protective action in the form of restrictions on activity concentration might need to be considered, particularly if the reference level, typically a dose of 1 mSv/a to a member of the public, was exceeded. The activity concentrations of ^{238}U and ^{210}Pb in DCP produced via the hydrochloric acid route are elevated (see Table 29). Although DCP is diluted considerably when fed to animals, the extent to which ^{210}Pb (along with ^{210}Po, which grows back into equilibrium with ^{210}Pb) may enter the human food chain has been raised as a concern. An investigation of ^{210}Pb and ^{210}Po in chickens fed on a diet supplemented by DCP is reported in Refs [25, 121]. The chickens were fed on diets of 2.5% DCP (containing ^{210}Pb and ^{210}Po, each at an activity concentration of 0.06 Bq/g) and 5% DCP (containing ^{210}Pb and ^{210}Po, each at an activity concentration of 0.11 Bq/g). It was found that 95% of the ingested activity was excreted immediately. The remaining ^{210}Pb accumulated mostly in the bone, to an activity concentration of up to 0.012 Bq/g, while the remaining ^{210}Po accumulated in the liver (up to 0.05 Bq/g) and kidneys (up to 0.22 Bq/g). Modelling of the ingestion pathway for chicken consumption by humans gave a maximum ingestion dose of 0.011 mSv/a [25].

9.5. REGULATORY CONSIDERATIONS

Radionuclide concentrations exceeding 1 Bq/g may be found in the phosphoric acid feedstock, the phosphate rock feedstock (in TCP production), the solid waste (from the hydrochloric acid process route) and in some animal feed products. In terms of the Standards, therefore, the manufacture and use of animal feed phosphates needs to be considered for regulatory control as a practice. The results of dose assessments show that the annual doses received by workers and by members of the public do not exceed 1 mSv. However, control needs to be exercised over liquid discharges and the disposal of sludge residues. The most appropriate regulatory option for the manufacturing process would seem to be a requirement for authorization in the form of a registration. The consumption of animal feed phosphates does not need to be subject to any restrictions in terms of the requirements for existing exposure situations.

The radionuclide activity concentrations in the process materials and products are such that, with the possible exception of some solid wastes, the transport of these materials would fall outside the scope of application of the Transport Regulations.

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10. PHOSPHOGYPSUM

10.1. INTRODUCTION

The digestion of phosphate rock with sulphuric acid generates the co-products phosphoric acid and phosphogypsum (see Section 5.1.1). For every tonne of P_2O_5 produced as phosphoric acid, 4–6 t dry mass of phosphogypsum is produced. The material mass ratio is even greater in practice because of the moisture content of phosphogypsum in its freshly processed state. For instance, phosphogypsum produced from the processing of Florida phosphate rock has a dry mass of about 5.2 t and a wet mass of 6.5 t for every tonne of phosphoric acid produced. The current annual production of phosphogypsum worldwide is about 160 million t, of which 40 million t (25%) is produced in the USA. Production is increasing worldwide and could reach 200–250 million t within the next decade or two. The total amount of phosphogypsum produced up to 2006 is estimated to have been about 6 billion t, of which 2.2 billion t (37%) was produced in the USA [33].

Depending on the particular wet process method employed (see Appendix V), phosphogypsum is produced in either the dihydrate form ($CaSO_4 \cdot 2H_2O$) or the hemihydrate form ($CaSO_4 \cdot ½H_2O$). Dihydrate methods were generally favoured in the past, especially in the USA, but hemihydrate methods are now gaining in popularity since they produce phosphoric acid of a higher strength. In the presence of free water, the hemihydrate form will quite rapidly convert to the dihydrate form and, if left undisturbed, will settle into a relatively hard cemented mass.

From the initial adoption of the wet process, phosphogypsum has enjoyed a wide range of uses, especially in agricultural and construction applications. However, in view of the large quantities produced and the seasonal nature of agricultural demand, production has far exceeded demand, resulting in two main alternative management approaches for surplus phosphogypsum:

(i) Stockpiling in large, above ground containment structures known as stacks (see Fig. 28), allowing the material to be used at a later time;
(ii) Discharging to water bodies, usually large rivers, river estuaries or the sea, thus permanently disposing of the material.

Progressive changes in environmental regulation, notably within the European Union in the 1990s and more recently under the London Convention of the International Maritime Organisation [124], have largely brought the discharge of phosphogypsum to water bodies to an end, causing considerably more

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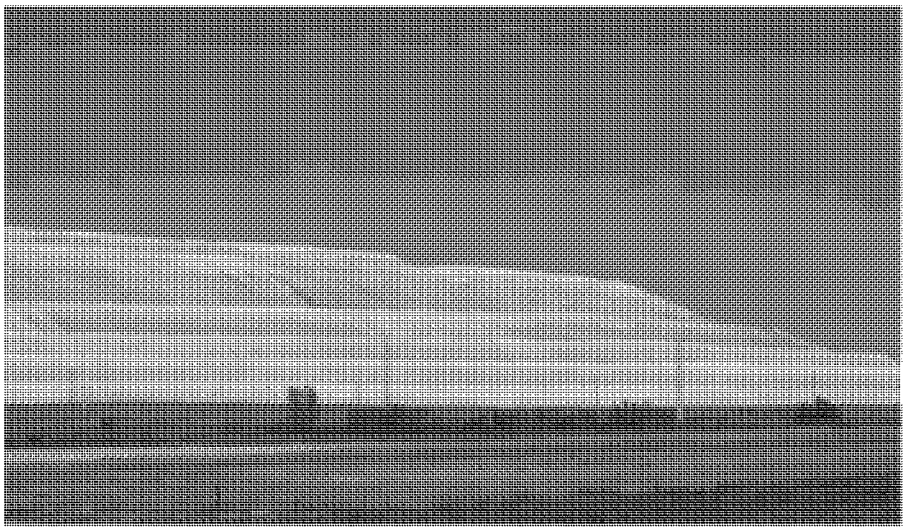

FIG. 28. A phosphogypsum stack in central Florida, USA (courtesy: Florida Industrial and Phosphate Research Institute).

phosphogypsum to be stored on land. In addition, while the use of phosphogypsum continues in several parts of the world, concerns about its radioactivity content and, to a lesser extent, its heavy metals content, have led to restrictions on the use of phosphogypsum in some markets, even though such concerns do not always have a proper scientific foundation. This has resulted in phosphogypsum stacks being, in effect, turned from short term holding piles into long term disposal facilities [125]. It has been estimated that, by 2006, a total of 2.6–3.7 billion t of phosphogypsum had been accumulated in stacks worldwide, representing 44–62% of the total amount of phosphogypsum produced up to that time. The corresponding figure for the USA (mostly in Florida) was 1.7 billion t, representing approximately half of the worldwide total. An overview of what has happened to all the phosphogypsum produced up to the year 2006 is given in Table 32. In estimating the amounts involved, a significant level of uncertainty relates to countries outside the USA concerning the amounts of phosphogypsum discharged, used or abandoned relative to the amount retained in stacks. Consequently, two estimates for these countries are given in Table 32. In the 'minimum stockpile' estimate, it is assumed that the amount of phosphogypsum that has been discharged is at the upper bound of the estimated range and that 25% of the remaining phosphogypsum has been used or abandoned, both assumptions leading to a minimum estimate of the amount stockpiled. In the 'maximum stockpile' estimate, it is assumed that the amount discharged is at the

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TABLE 32. CUMULATIVE AMOUNTS OF PHOSPHOGYPSUM UP TO 2006

Location	'Minimum stockpile' estimate		'Maximum stockpile' estimate	
	Amount (billion t)	Proportion of total (%)	Amount (billion t)	Proportion of total (%)
Stockpiled in stacks:				
USA	1.7	29	1.7	29
Other countries	0.9	16	2.0	34
Total	2.6	44	3.7	62
Discharged to water bodies:				
USA	0.5	8	0.5	8
Other countries	2.5	42	1.3	21
Total	3.0	50	1.8	29
Used or abandoned	0.3	5	0.5	8
Total amount produced	6.0	100	6.0	100

lower bound of the estimated range and that only 20% of the balance has been used or abandoned, both assumptions leading to a maximum estimate of the amount stockpiled.

Phosphogypsum is currently being added to stacks at an annual rate of about 40 million t in the USA and 90 million t elsewhere. At these rates, the total amount of phosphogypsum stored in stacks will more than double to 7–8 billion t by 2040. Most of this growth will occur in countries with developing economies, where a three- or fourfold increase can be predicted from current growth patterns. The actual growth is likely to be faster because of further reductions in discharges to water bodies and increased phosphogypsum production. Assuming a complete cessation of discharges to water bodies and an increase in phosphogypsum production from 160 to 240 million t per year, the projected total of 7–8 billion t would be reached by 2025, that is, 15 years earlier.

In addition to the phosphogypsum itself, very large volumes of highly acidic process water (also known as pond water) are associated with phosphogypsum production. Billions of litres of this water are stored on top of, and in, active stacks (see Fig. 29).

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FIG. 29. Storage of process water on a phosphogypsum stack at Huelva, Spain.

The indefinite stacking of phosphogypsum has negative impacts in terms of the engineering and environmental aspects of the stacks themselves and the associated costs and long term liabilities [83, 126]. These negative impacts were not fully appreciated in the past, but awareness of them has been growing for some time. A good example of this can be found in the USA, where the costs of closing certain older phosphogypsum stacks under locally binding regulations [127], notably in central Florida, have become very high, not least because the stacks were not designed and constructed in accordance with current standards and the use of liners to prevent groundwater contamination was not yet mandatory [128]. Furthermore, the costs of closure have fallen on taxpayers rather than on the owning companies because the stacks in question had been abandoned after the companies went into liquidation [33]. As a result, new stacks either have to be reported as liabilities in the financial statements of the owning company or subject to a minimum bond of US $150 million to cover the costs of future closure and ongoing maintenance.

This awareness of the negative impacts of indefinite stacking and the huge increases in the amounts of phosphogypsum having to be stored in stacks in the future have highlighted the need for a systematic reappraisal of the merits of, and potential for, increased use of phosphogypsum worldwide. At present, the use of phosphogypsum accounts for only a very small proportion of the amount

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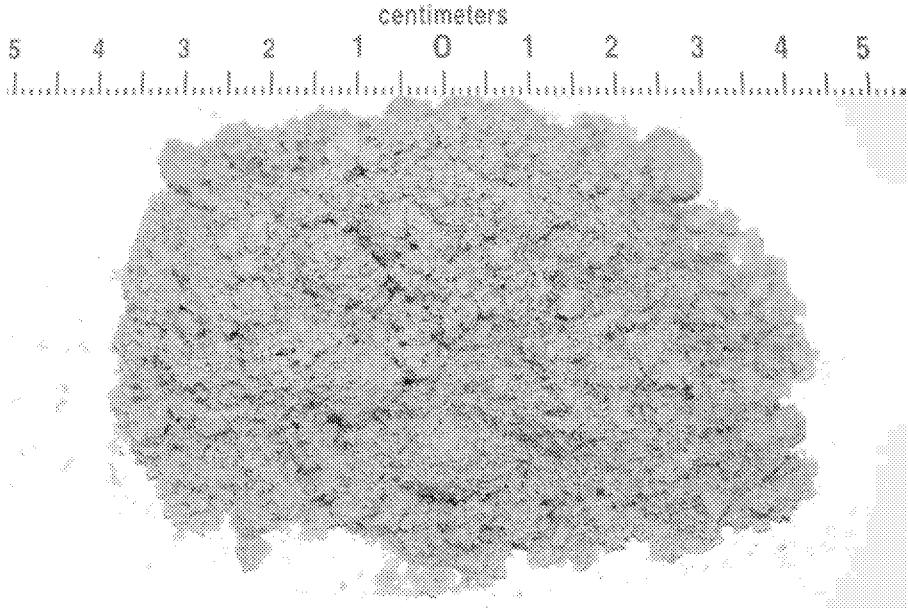

FIG. 30. Phosphogypsum.

produced (probably much less than 5%). In addition, attention is now being drawn to the potential benefits that might be derived from innovations in wet process phosphoric acid production that could reduce the operational requirements for stacks and the large ponds associated with them.

10.2. PHYSICAL AND CHEMICAL PROPERTIES

Phosphogypsum is a damp, silty or silty sand sized material (see Fig. 30). Dihydrate phosphogypsum consists primarily of silt size, relatively soft aggregates of crystals, the morphology of which depends on the source of the phosphate rock and the reaction conditions in the attack tank. The maximum particle size varies from approximately 0.5 mm (no. 40 sieve size) to 1.0 mm (no. 20 sieve size) and typically 50–75% of the material passes through a 0.075 mm (no. 200 sieve size) screen. The silty size range of dihydrate phosphogypsum classifies it as an A-4 soil in the AASHTO[20] soil classification system [129].

[20] AASHTO: American Association of State Highway and Transport Officials.

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Hemihydrate phosphogypsum generally has a larger particle size than the dihydrate form.

The moisture content is usually in the range 8–30%. For maximum density, the optimum moisture content of phosphogypsum (dihydrate or hemihydrate) lies in the range 15–20% [130]. Typical engineering properties of phosphogypsum such as density, strength, compressibility and permeability (hydraulic conductivity) can be found in Refs [130–132]. These properties are influenced not only by the characteristics of the source rock and the reaction process, but also by the method of deposition, age, location and depth within the stack in which the phosphogypsum is found. Owing to the homogeneous nature of phosphogypsum particles, the stacking process causes the material to become compacted over time. Thus, the density and strength of the material generally increase with the age of the stack and the depth within the stack, while the compressibility and permeability are likely to show a corresponding decrease. However, this effect may be compromised by the presence of voids created by dissolution channels and cavities caused by rainfall infiltration. The specific gravity of phosphogypsum produced in Florida, USA, is typically 2.3–2.6, while the upper bound of the range of dry densities is likely to lie in the range 1.47–1.67 g/cm^3, based on standard Proctor compaction (a laboratory method to determine, experimentally, the dry densities of soil) [130]. Values for phosphogypsum produced elsewhere may be slightly different. The addition of fly ash or Portland cement to phosphogypsum yields a mixture known as stabilized phosphogypsum that has slightly higher values of maximum dry density and optimum moisture content [133].

In terms of shear strength, phosphogypsum in its unconsolidated, undrained and unstabilized form typically exhibits an average internal friction angle of 32° and a cohesion value of 125 kPa. For cement stabilized phosphogypsum, the corresponding values are 28–47° and 76–179 kPa, respectively [134]. Unstabilized phosphogypsum has a permeability coefficient of 2.1–13 × 10^{-5} cm/s.

In addition to calcium sulphate, the main constituent, phosphogypsum contains alkali fluosilicates (Na_2SiF_6 and $NaKSiF_6$), chukhrovite ($Ca_4SO_4SiAlF_{13}\cdot nH_2O$) — a complex iron phosphate ($Fe_3(NH_4,K,H)H_8(PO_4)_6\cdot 6H_2O$), the majority of which is in the ammonium form — and many other possible compounds [135]. A comparison of the major constituent concentrations in phosphogypsum with those in the phosphate rock from which it is derived helps to determine the effectiveness of the sulphuric acid digestion process. A knowledge of these concentrations can also be useful in matching phosphogypsum types to end uses, especially in agricultural applications where specific nutrients, such as zinc, within the phosphogypsum can be used to remedy specific soil deficiencies [136]. Published data on the main chemical constituents of phosphogypsum are given in Appendix VI. Obviously, calcium and sulphate are the major constituents and

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together they account for up to 92% of the total content. Analyses have indicated the presence of sodium, magnesium, aluminium and iron, apart from silica and P_2O_5. The silica content of phosphogypsum is 0.5–18%, depending upon the rock source and the efficiency of the wet process. Phosphogypsum also contains fluorides, at concentrations of 0.1–1.8%. Fluoride concentrations may be significantly reduced by effective washing of the phosphogypsum before use or disposal. Since calcium sulphate is the major constituent, phosphogypsum is acidic in nature and the acidity is increased further as a result of contamination with residual phosphoric, sulphuric and hydrofluosilicic acids. For instance, phosphogypsum produced in the USA has pH values in the range 2.5–6. The aim is for most of the P_2O_5 in the phosphate rock feedstock to be recovered as phosphoric acid and, in pursuit of this aim, the trend is towards reduced amounts of residual P_2O_5 within the phosphogypsum. Nevertheless, phosphogypsum may still contain 5–20 times more phosphorus than is present in natural soils and sediments.

A knowledge of the concentrations of impurities in phosphogypsum can be important for defining technical solutions for the production of a marketable product and the consequent management and environmental policies for its storage in stacks. The concentrations of most trace elements in phosphogypsum are significantly lower than those in the source rock, even after allowing for the fact that the digestion of 1 t of rock typically produces 1.46 t of phosphogypsum. This implies that the trace elements tend to migrate with the P_2O_5 fraction to the phosphoric acid. Small amounts of radioactive elements, such as radium and uranium, and of (non-radioactive) heavy metals, such as arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver, as well as phytotoxic fluoride and aluminium, are present in phosphogypsum and its pore water [76]. The concentrations of these impurities vary widely, depending on the composition of the phosphate rock used as feedstock [75, 78] and, to a lesser extent, on other factors, such as differences in operation of the processing plant [137]. With some exceptions, the concentrations of cadmium and other heavy metals in phosphogypsum derived from igneous phosphate ore tend to be lower than those in phosphogypsum derived from sedimentary ore, while the concentrations of lanthanides (rare earth elements) tend to be higher. Published data on heavy metal concentrations and rare earth elements in phosphogypsum are given in Appendix VI. It has been observed that heavy metals tend to concentrate in particles smaller than 20 μm, and it is in this size fraction that the most significant variations in concentration are to be found, depending on the characteristics of the source rock [138, 139].

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10.3. RADIONUCLIDE ACTIVITY CONCENTRATIONS

All the constituent minerals in phosphogypsum listed in Section 10.2, especially the main constituent, calcium sulphate, can be expected to exhibit radionuclide substitutions. The primary substitution compounds are thought to be sulphates in the form of radium sulphate, lead sulphate, lead disulphate, polonium disulphate and thorium disulphate. The mineral chukhrovite ($Ca_4SO_4SiAlF_{13} \cdot nH_2O$), a constituent of phosphogypsum, is known for having a relatively high radium content owing to the substitution of radium for calcium [17]. The radionuclides known or suspected of concentrating in phosphogypsum can also form fluorides, oxides, hydrides and sulphides.

A small amount of uranium in the U^{4+} ionic form migrates to the phosphogypsum owing to four main reasons:

(i) Unreacted rock particles containing U^{4+} become coated with phosphogypsum;
(ii) Some substitution by U^{4+} occurs in the crystal lattice of phosphogypsum;
(iii) Residual amounts of phosphoric acid, containing uranium phosphate, remain with the phosphogypsum after filtration and transport to the stack;
(iv) U^{4+} may adsorb on to the surface of phosphogypsum as UO_2HPO_4.

The residual phosphoric acid remaining with the phosphogypsum may also contain a small amount of uranium in the form of uranyl ions (UO_2^{2+}). Moreover, substitution of Ca^{2+} ions by uranyl ions may occur on the surface of the phosphogypsum crystal lattice [140].

Data on radionuclide activity concentrations in phosphogypsum are given in Appendix VI. The activity concentrations of ^{238}U are mostly below 0.1 Bq/g, with occasional higher values possibly indicative of lower recovery levels of phosphate in the attack tank due to some degree of inefficiency in the process. The activity concentrations of ^{226}Ra and its progeny are generally in the range 0.2–3 Bq/g for material derived from sedimentary phosphate ore. The ^{226}Ra concentrations in phosphogypsum derived from igneous ore are lower, ranging from less than 0.01 to 0.7 Bq/g. The worldwide distribution of ^{226}Ra activity concentrations, estimated by fitting a lognormal curve to the available data, is shown in Fig. 31. The arithmetic mean of the distribution is 1 Bq/g. Activity concentrations vary between stacks and even between different levels in stacks, depending on factors such as age and source rock characteristics.

There is potential for the removal of some of the radionuclides from phosphogypsum while it is still in slurry form. Reduction of the radionuclide content using a cyclone has been attempted on the basis of indications that a higher proportion of the radioactivity is to be found in the fine fraction, although

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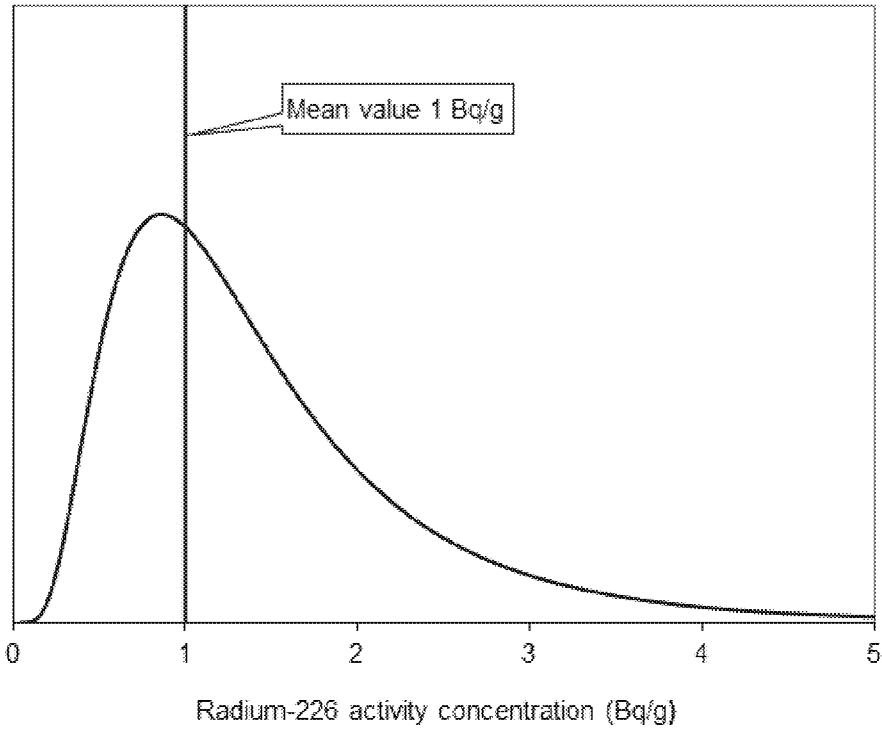

FIG. 31. Estimated worldwide distribution of ^{226}Ra activity concentrations in phosphogypsum.

this is not supported by more recent data [141]. The sulphates of radium and calcium differ in ionic radius, crystalline structure and solubility (calcium sulphate is slightly soluble and radium sulphate is highly insoluble) [142] and thus would not be expected to co-crystallize.

Any large scale radiochemical purification of phosphogypsum is dependent on economic factors. A process known as the Merseberg ammonocarbonation process yields ammonium sulphate, an excellent fertilizer, and calcium carbonate, a useful product for neutralization of acidic water. This process has been used on a commercial scale in China, India and Indonesia. Almost all the radioactivity within the phosphogypsum migrates to the calcium carbonate, leaving the ammonium sulphate fertilizer product lower in radioactivity than most natural materials. However, the process has enjoyed only limited use because of abundant supplies of inexpensive ammonium sulphate from other industries.

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10.4. STORAGE OF PHOSPHOGYPSUM

The amounts of phosphogypsum stored in stacks are vast (approximately 3 billion t worldwide). There are stacks of various sizes in well over 50 countries, of which the largest cover land areas measured in square kilometres. In Florida, USA, for instance, there are some 25 stacks covering a land area of more than 50 km^2 [143], implying an average area of more than 2 km^2 per stack. The management of phosphogypsum stacks requires care because of the large volumes and land areas involved, the potential for emissions of dust and radon gas to the atmosphere and the potential for seepages containing fluorides, heavy metals (such as cadmium) and, to a lesser extent, radionuclides. The management approach for phosphogypsum stacks is no different in principle from that for engineered structures containing other types of NORM in bulk amounts, such as residues (tailings and waste rock) from the mining of radioactive ores. This management approach is described in Ref. [5]. The following basic measures help to mitigate or prevent any negative impact:

(a) The provision of perimeter systems to contain possible leaks or spills;
(b) The use of suitable liners to prevent contamination of groundwater [144];
(c) The provision of a well-maintained water cover to reduce airborne emissions of dust and radon gas;
(d) The provision of a system of dust suppression in the case where it is not feasible to provide a water cover, either by keeping the material wet or by planting grass or other light vegetation (although the establishment of vegetation may increase the rate of radon emission).

There are two methods of stacking: wet stacking and dry stacking. The wet stacking method is the more common of the two. It is used by most of the plants that produce dihydrate phosphogypsum and by several plants producing hemihydrate phosphogypsum [145, 146]. In the latter case, the free water associated with the use of the wet stacking method causes the hemihydrate material to convert to the dihydrate form (see Section 5.1.1.1). Although the conversion is not complete by the time the slurry reaches the stack, the management approach, in terms of the methods and equipment used, is the same as that for stacking phosphogypsum from dihydrate plants. Where water is available at a reasonable cost, wet stacking is easier, more reliable and less costly to carry out than dry stacking. It has a further economic benefit in that P_2O_5 recovery is improved if the water is recycled back to the process. Unlike dry stacking, wet stacking does not involve 'construction around the clock' and can be carried out with significantly less equipment and fewer personnel. Airborne dust generation, which can be a problem with dry stacking, is generally not a

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problem with wet stacking because most of the surface area remains wet. Perimeter and internal partition dykes cover relatively limited and defined areas, and construction traffic is restricted to specific maintenance and access roads that are relatively easy to keep damp.

10.4.1. Wet stacking

In wet stacking operations (see Fig. 29), the phosphogypsum is mixed with water as it leaves the filtration system and is pumped as a slurry through a pipeline to a holding area within the stack where the solids settle out.

10.4.1.1. Water circuit

The water associated with wet stacking is managed either as a closed circuit (recirculating) system or an open circuit (once through) system:

(a) In closed circuit systems, process water, also known as pond water, is used for transporting the phosphogypsum to the stack at a typical solids content of 20–30%. The water is clarified by allowing the solids to settle and is then decanted and pumped back to the plant, where it is reused for slurrying the phosphogypsum or for other process applications. The recirculated process water becomes more acidic over time, usually reaching an equilibrium pH somewhere within the range 1–2, depending on process and climatic variables. The soluble P_2O_5 content of the acidic process water typically reaches 10 000–25 000 mg/L, but can be as high as 35 000 mg/L. Recirculated water can be used to wash the filters and re-slurry the gypsum cake to recover P_2O_5. Washing with high P_2O_5 content water improves P_2O_5 recovery, which is one of the significant advantages of wet stacking. In a wet stack, the operator recovers soluble P_2O_5 from water entrained in the gypsum cake, with some additional P_2O_5 recovery from unreacted rock over time, as well as P_2O_5 contained in plant spills diverted to the pond. It is not uncommon to improve P_2O_5 recovery in a wet stack by as much as 3%. In wet climates, excess water due to rain may sometimes give rise to the need for additional treatment before discharging to a receiving water body.

(b) In open circuit systems, the water used for generating the slurry, rather than being recirculated, is discharged as an effluent containing phosphates, fluorides and suspended solids. At coastal locations, the water may be extracted from the sea and discharged back to the sea after clarification. Seawater slurries are usually very dilute (about 5% solids by weight) and the pH of the water being discharged is greater than 2.

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In the light of experience gained from the treatment of the highly acidic process water associated with closed circuit systems [147] and from dealing with spills in locations such as Florida and Louisiana, USA [33], it has been argued that the use of fresh water rather than recirculated water for creating the slurry would bring about significant environmental protection benefits, especially if the phosphogypsum is first washed with fresh water. Open circuit operation may also be favoured for other reasons; in arid climates, closed circuit operation may not be feasible because of evaporation from the pond, while in other situations, open circuit operation may be the more attractive option because of the existence of a large, nearby body of water, such as the sea. Nevertheless, closed circuit systems are generally preferred to open circuit systems because they do not generate liquid effluent.

Some phosphogypsum stacks have been converted from seawater (open circuit) systems to process water (closed circuit) systems. After conversion, the water returned to the plant from the stack is, initially at least, highly corrosive because of contamination with chlorides leached from the previously deposited phosphogypsum. Special measures would have been needed to reduce such contamination. The use of seawater at production facilities in Greece, Mexico, Spain and Tunisia has progressively stopped, although in most cases not as a result of decisions to convert to closed circuit systems but rather because of plant closure for financial reasons unrelated to the choice of water management system. In some cases, the change has been driven by the need to conform with environmental regulations, such as in Mexico and Tunisia, while in others the cost of changing process to achieve compliance has been so high that the production facility has simply closed altogether. In Spain, a change was made in the late 1990s from partial (20%) discharge to a closed circuit driven by the desire to eliminate completely any negative impact from process waters used for transporting phosphogypsum to the stacks.

10.4.1.2. Construction and operation of stacks

The stack perimeter is established by constructing 'starter dykes'. Control of the slurry within the stack during operation is achieved using a technique known as elevated rim ditching, as illustrated in Fig. 32, and a system of pipes and valves, known as spigots, that direct the phosphogypsum slurry to various places on the top of the stack (see Fig. 33). The construction of starter dykes and rim ditches is usually carried out using earthmoving equipment, as shown in Figs 32 and 34. The use of wet gypsum for construction work avoids the generation of airborne dust. The emission of dust from maintenance and access roads as a result of their use by construction traffic is controlled by keeping the roads damp.

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FIG. 32. Elevated rim ditching.

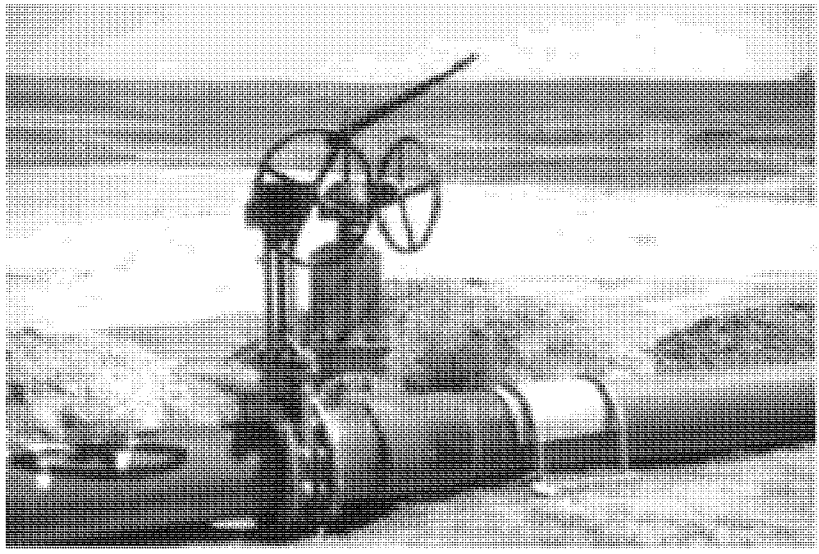

FIG. 33. Pipes and valves (spigots) for control of slurry on a stack.

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FIG. 34. Stack construction work using wet phosphogypsum.

For safety reasons, rim ditches are constructed in accordance with specific geometric requirements and construction techniques, ensuring that all the rain that falls on the slurry ponds during operation is contained. A specified freeboard needs to be maintained to prevent the rim dams from being breeched by wave action in windy conditions. In Florida, USA, the freeboard requirement had to be increased following a succession of severe rainfall events which led to the near overflow of a stack at Piney Point in 2002 (see Fig. 35) [148].

A ditch or channel usually surrounds the stack to retain any lateral seepage at the toe of the stack and rainfall runoff contaminated by contact with non-vegetated side slopes. This ditch or channel may also serve as a process water cooling pond. A process water management system at a stack in Spain is shown in Fig. 36. In wet climates, excess water in the ditch or channel may be returned to the chemical plant as process make-up water or pumped to the top of the stack for storage, from where it is eventually consumed as process water or discharged to a receiving water body after appropriate treatment. The treatment of excess water usually consists of two-stage lime neutralization and clarification. The treated water contains high concentrations of dissolved solids, sulphate and sometimes ammonia. Process water that has not been in contact with phosphogypsum can,

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FIG. 35. Pond near to overflow at Piney Point, Florida, USA, in 2002.

FIG. 36. Process water pond and perimeter channel at a phosphogypsum stack at Huelva, Spain.

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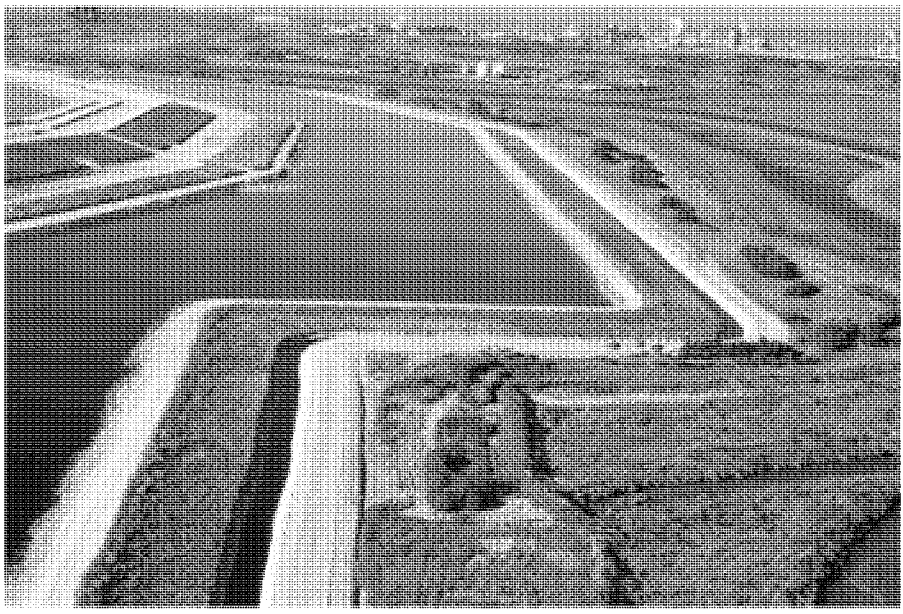

FIG. 37. Vegetation of side slopes at a phosphogypsum stack at Huelva, Spain.

alternatively, be treated using reverse osmosis. The quantity of excess process water needing to be treated and discharged can usually be reduced, and possibly even eliminated, by having adequate surge capacity and by following appropriate procedures for the operation of the phosphogypsum stack and the chemical plant. For example, by conditioning and vegetating the bare stack slopes, as illustrated in Fig. 37, rainfall can, over time, be prevented from coming into contact with the phosphogypsum, thus avoiding contamination and enabling side slope runoff to be segregated and discharged without treatment.

10.4.1.3. Control of groundwater contamination

Contamination of groundwater by seepage from phosphogypsum stacks is an obvious environmental concern and it is common for new stacks to be constructed with an impervious bottom liner over a drain field that can be monitored for possible liner leakage. A typical stack liner is shown in Fig. 38. Measures for containing seepage from existing stacks can be implemented retrospectively. In some situations, a vertical hydraulic barrier comprising a soil–bentonite cut-off wall, or 'slurry wall', is built around the perimeter of the site, along with pressure relief wells. In other situations, a high density polyethylene (HDPE) geomembrane is installed on top of the stack, in order to serve as a bottom liner for subsequent deposits of wet phosphogypsum.

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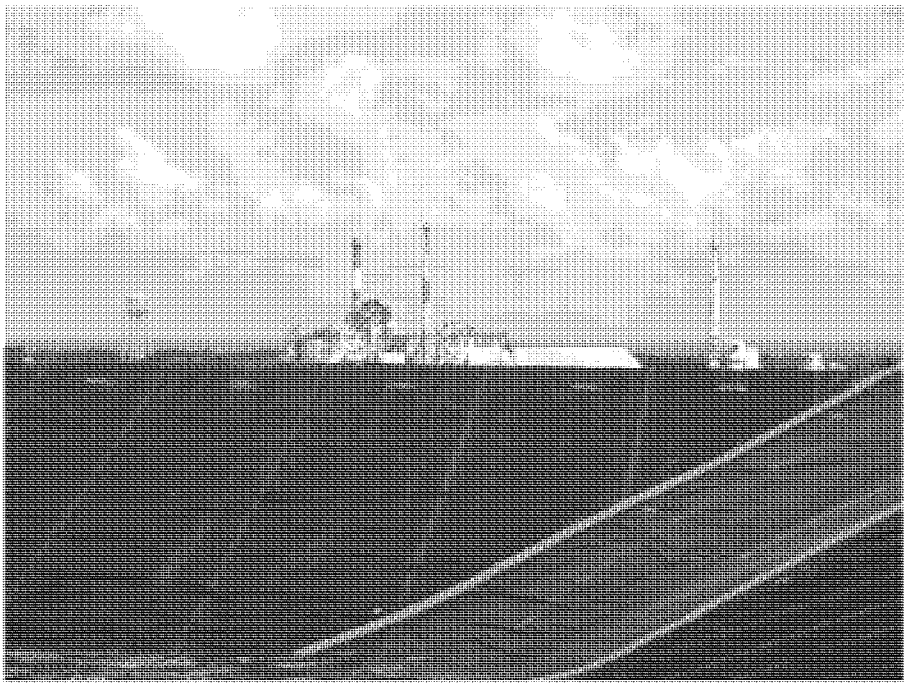

FIG. 38. Liner for a phosphogypsum stack.

In some regulatory jurisdictions, the use of a liner is a legal requirement. In Florida, USA, for instance, unless it had been demonstrated that groundwater impacts would be contained indefinitely within the property line or within a designated zone of discharge, all existing stacks and associated process water ponds had to undergo engineering modifications to contain any seepage or be closed and replaced by new lined facilities. Furthermore, all new stacks now have to include an impervious bottom composite liner system, consisting of an HDPE geomembrane 1.5 mm thick in combination with either a compacted clay layer beneath it or a compacted gypsum layer above it [149]. Nevertheless, it would appear that, depending on the conditions at the site, a liner is not always essential for controlling seepage. After many years of operation of stacks without liners, such as those at Huelva, Spain, it has been demonstrated that in many cases the substrate underlying the stack has remained impermeable and this, together with the inherent properties of phosphogypsum to form a largely impermeable compacted base, has resulted in there being little difference between lined and unlined stacks in terms of their potential for groundwater contamination. In Florida, USA, an evaluation of groundwater impacts from unlined stacks showed that heavy metals and radionuclides in the seepage water are attenuated by the

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FIG. 39. A major sinkhole in an active phosphogypsum stack [33].

fine grained soils and calcareous strata upon which most of these structures are built [83, 150–152].

10.4.1.4. Control of fluoride emissions to the atmosphere

Fluorides, mainly in the form of hydrogen fluoride, are emitted from phosphogypsum pond water surfaces. These emissions can be reduced significantly if fluosilicic acid is extracted during the phosphoric acid production process.

10.4.1.5. Structural failures of stacks

Among the more spectacular problems associated with wet stacking is the occurrence of massive sinkholes, of which there have been four or five in Florida, USA, alone. Even a lined stack of modern design cannot cope with sinkholes of the size shown in Figs 39 and 40. Wet stacking of phosphogypsum is usually governed by regulations that typically require an extensive investigation of the subterranean conditions to determine the potential for sinkholes.

There have also been major spillages of acidic water due to structural failures of pond retention systems. While such failures are relatively rare, they

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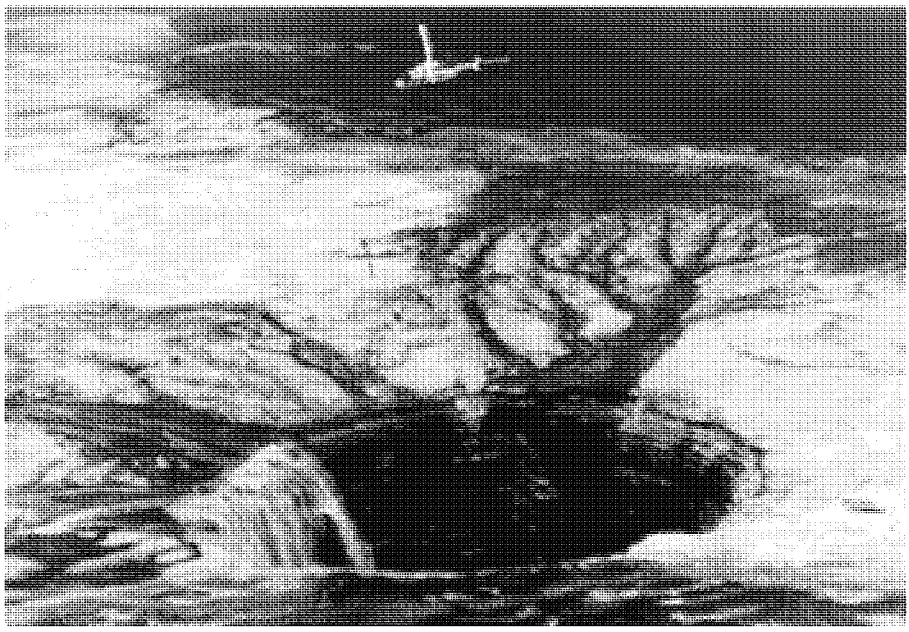

FIG. 40. A sinkhole in a phosphogypsum stack (helicopter gives a sense of scale) [33].

may have a significant impact on surface water bodies, more as a result of the acidic nature of the water than as a result of its radionuclide content [33].

Examples of events occurring in the USA involving failure or near failure are the following:

(a) In 1997, tens of thousands of cubic metres of acidic water escaped from a stack in Florida and polluted a nearby river.[21]

(b) In 2002, at a facility in Florida, a combination of extreme weather events and neglect caused by the bankruptcy of the owning company led to the near overflow of a stack, which would have resulted in total stack failure in a highly environmentally sensitive area. The only remedy was the emergency discharge of neutralized water by barge far out to sea, which was undertaken at very great cost.

[21] State and local agencies are providing over $1 million to restore, preserve and improve the estuarine habitats in the affected Alafia River and adjacent areas of Tampa Bay into which the river flows. The Alafia River Spill/Mulberry Phosphate Restoration Council that was formed to aid the river's environmental recovery announced that it would fund estuarine restoration projects to improve the habitat along the Alafia River (see, for example, http://www.floridadep.com/southwest/news/101003.htm).

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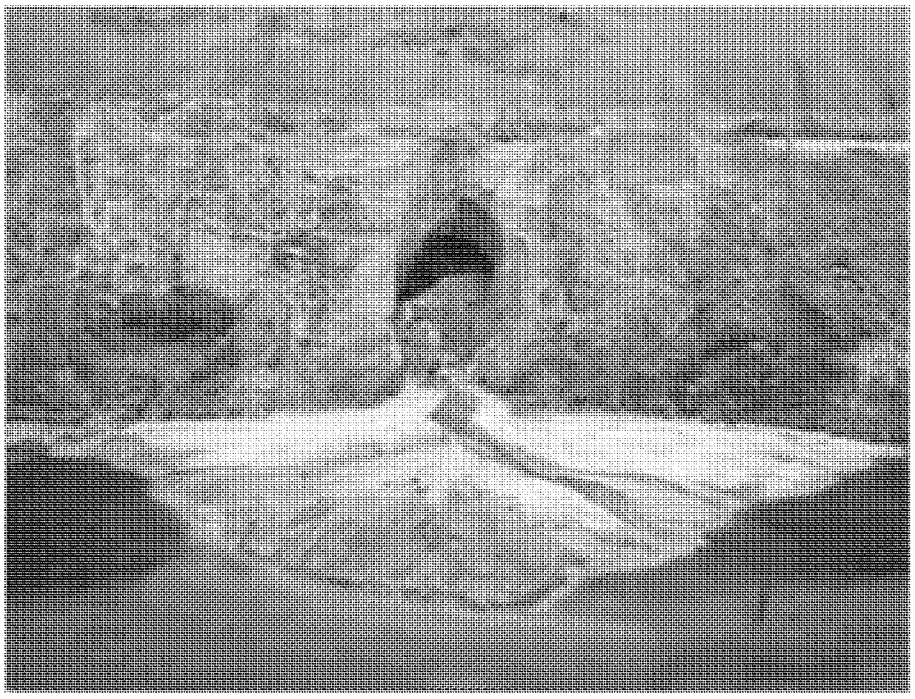

FIG. 41. Side slope failure at Piney Point, Florida, USA, in 2003 (courtesy: Florida Department of Environmental Protection).

(c) In 2004, 227 000 m^3 of acidic water escaped from a stack, also in Florida, into a neighbouring creek. The apparent cause was damage done to the pond wall by waves driven by the force of a hurricane that hit the area.

(d) In 2004, there was a spill from a stack in Florida, which fortunately did not extend beyond the property.

(e) In 2005, about 65 000 m^3 of acidic water escaped from a stack in Mississippi into surrounding marshland. The company argued that excessive rainfall was the cause, while state officials believed it was an error on the part of the company in trying to fill the process water pond too rapidly.

Other failures associated with stacks of modern design include side slope failure (see Fig. 41) and liner breaches, which by comparison are relatively inexpensive to deal with.

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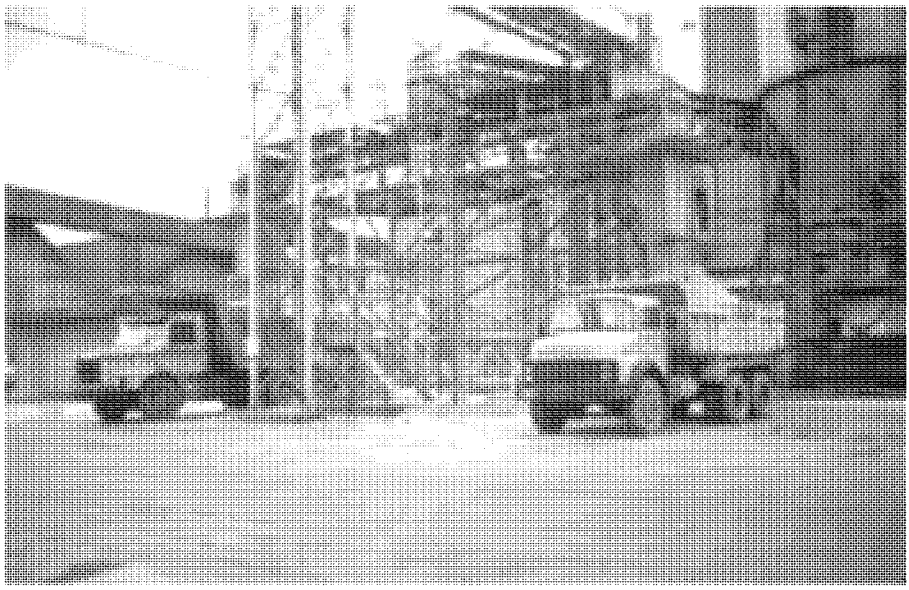

FIG. 42. Loading of phosphogypsum into trucks [146].

10.4.2. Dry stacking

In dry stacking operations, phosphogypsum leaving the filtration system is transported to the stack by belt conveyor or truck, without the addition of water (see Fig. 42). Upon reaching the stack, the material is deposited and spread using equipment such as mechanical stackers, movable belt conveyors and bulldozers (see Fig. 43). Dry stacking, although less widely practised than wet stacking, has been carried out in various parts of the world, including Brazil, Jordan, Senegal, Tunisia and several countries of the former Soviet Union. In Jordan, dry stacking is practised at Aqaba for dihydrate phosphogypsum and at Eshidiya for hemihydrate phosphogypsum.

The moisture content of the phosphogypsum emerging from the filtration system is sufficient to prevent the emission of airborne dust from the material while it is being transported on belt conveyors or in trucks. However, the spillage of phosphogypsum from conveyor belts and trucks, as well as at any transfer points, is a potential source of airborne dust if the spilt material is allowed to dry before being removed. For this reason, the conveyor may need to be enclosed. The use of a high pressure water spray on the underside of the conveyor at the discharge end removes any phosphogypsum adhering to the belt. The wash water from the spray system is collected and consumed as process water or appropriately treated and discharged.

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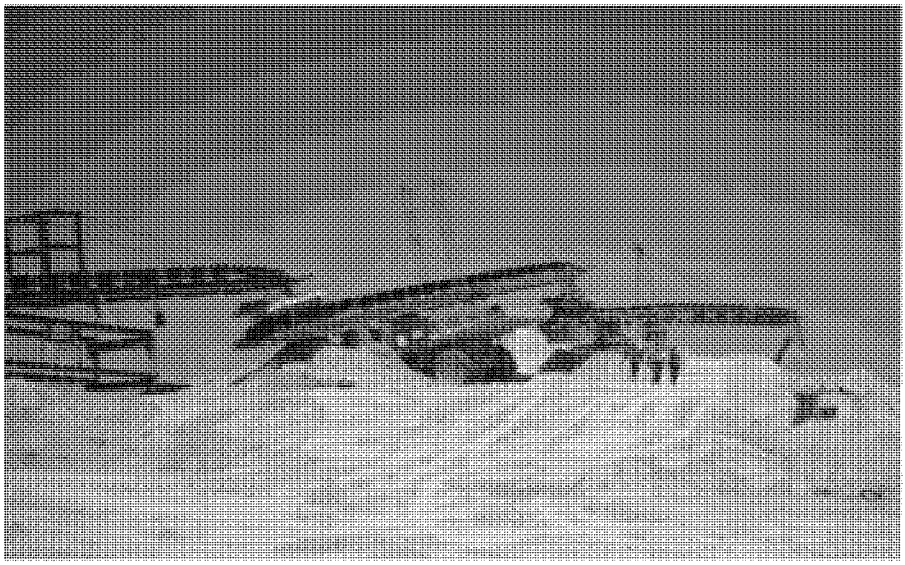

FIG. 43. Spreading of phosphogypsum in a dry stacking operation.

When dry stacking operations are carried out in areas with unusually high rainfall, such as at Santos, Brazil, where the average annual rainfall is 3 m, the stack surfaces remain permanently damp and no significant emissions of airborne dust occur. In less extreme climatic conditions, the stack surfaces dry out between periods of rainfall. A thin, fragile crust forms on the stack surface, which can help to minimize the emission of airborne dust as long as it remains undisturbed by the wind and by the construction equipment used for placing and spreading the phosphogypsum. The emission of airborne dust as a result of the disturbance of this crust creates not only a dust problem, but also leads to the emission of fluorides and radon that emanate from the surfaces of the dust particles. Dust emission from dry stacking operations (and the resulting fluoride and radon emissions) is controlled by limiting the extent of the active placement area and haul roads and by spraying the surfaces with water to keep them damp.

Rainfall runoff from the stack is collected and returned to the chemical process or used to suppress the emission of airborne dust from maintenance and access roads. Dry stacking does not eliminate the possibility of acidic seepage from the base of the stack and from the toe of the side slope. Even in desert climates, a bottom liner may need to be incorporated to prevent groundwater contamination because vertical cracks tend to form within the stack as a result of differential settlement and/or side slope instability. These cracks create paths for the entry of water deep into the stack during relatively rare heavy rainfall events. Filling of these cracks with phosphogypsum minimizes the entry of rainwater and

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also helps prevent possible slope instability caused by hydraulic pressures generated within the water filled cracks.

10.4.3. Environmental impacts

As explained in Sections 10.4.1 and 10.4.2, measures are taken during the construction and operation of phosphogypsum stacks to ensure that the runoff of contaminated rainwater is contained within the stack perimeter, that effluent water is treated before discharge and that seepage into the groundwater and emission of dust to the atmosphere are controlled. These measures are designed to keep the environmental impacts of phosphogypsum stacks within acceptable bounds. Contamination of groundwater near phosphogypsum stacks is, in any case, restricted by the limited solubility of radium and other radioactive species in sulphate form [81]. A detailed investigation was carried out on the processes responsible for controlling the interaction and release of radionuclides from phosphogypsum from a phosphogypsum stack at Piney Point Phosphates in Florida [81]. On the basis of measurements of activity concentrations in groundwater collected from several monitoring wells around the stack, it was concluded that various removal mechanisms, including adsorption within the stack, precipitation within the soil horizons just below the stack and interception of stack fluids by drainage ditches, prevent large scale migration of radionuclides to the underlying aquifer. However, some of the laboratory studies on the leaching characteristics of ^{226}Ra from phosphogypsum showed a dependence on various conditions such as solution:solid ratios, contact times and acidity on dissolution rates [153, 154]. Forced leaching experiments indicated that uranium dissolution largely depends on the presence of phosphoric acid traces in phosphogypsum. Studies indicated that the leaching of radium may be slow in field conditions near phophogypsum stacks, especially when the phosphogypsum is previously washed and stored.

An investigation of the impact of phosphogypsum stacks on surface water systems was carried out in the Cubatão region of southern Brazil [155]. Sediments were sampled from a river receiving effluent discharged from nearby phosphogypsum stacks. Near the point of discharge, the concentrations of barium, zirconium and thorium in the sediment were found to be elevated above local background levels. The samples also showed the presence of rare earth elements at elevated concentrations and with a higher degree of fractionation in comparison with the concentration ratios of individual rare earth elements in phosphate rock. The mean concentrations of cerium in surface and core sediments were 151 and 387 ppm, respectively, which may not be desirable in surface water streams. These results were consistent with the contaminants having originated from the phosphogypsum, the characteristics of which reflected

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the composition of the Catalão igneous phosphate ore, with some modification as a result of the phosphoric acid production process. The sediment contamination levels were found to decrease rapidly in the downstream direction, indicating that the influence of the phosphogypsum stacks was confined to a small area.

The emission of fluorides from ponds in wet stacking operations has been measured. The rate of emission was found to be in the range 0.01–0.10 $kg \cdot ha^{-1} \cdot d^{-1}$. Elevated levels of fluorides have been found in vegetation growing very close to a phosphogypsum stack [156]. The repeated ingestion of such vegetation by cattle over periods of years may cause fluorine toxicosis, also known as fluorosis or brittle bone syndrome.

In some countries, the recent spread of residential and commercial property development has resulted in members of the public living and working ever closer to phosphogypsum stacks. Some older stacks have now become surrounded by developed metropolitan areas. In Huelva, Spain, for instance, residential apartments are being built less than 300 m from an operating stack. Nevertheless, measurements have indicated that exposure levels diminish very rapidly with distance from the stack [94].

Measurements of radon concentrations in the air around phosphogypsum stacks have been reported from a few countries. The average radon concentration above a phosphogypsum stack in Huelva was recorded as 13.1 Bq/m^3 over a measurement period of six months and comparable with the natural background levels measured in the adjacent residential areas [157]. Measurements were also reported from a phosphogypsum stack in India [74]. The ^{222}Rn concentrations were 9–45 Bq/m^3 in the indoor environment, close to the stack, and were also comparable with the background concentrations in the local environment.

The radon emanation factor for phosphogypsum is typically about 0.2 [158]. Measurements of the emission of radon have been made on the surfaces of several phosphogypsum stacks in central Florida, USA [150, 151], and on one stack in south-western Spain [159]. The results are shown in Table 33. The Spanish study found that radon exhalation rates above the surface of a stack were an order of magnitude higher than those found in the reference site (agricultural soil), with no significant enhancement in radon exhalation rates during tillage or digging of the stack surface. However, since the stack surface is open to the atmosphere, no significant buildup of radon above the stack was observed.

Investigations have also been carried out at Huelva, Spain, on the aerosol activity concentrations above phosphogypsum stacks after preliminary restoration work [160]. The ^{238}U, ^{226}Ra and ^{210}Pb concentrations in airborne dust were 0.016, 0.01 and 0.6 mBq/m^3, respectively, and were comparable to background levels. The corresponding incremental inhalation dose received by maintenance workers was estimated to be 0.7 μSv/a. The formation of a hard crust on the surface of inactive stacks also prevents resuspension of particles and

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TABLE 33. RADON EMISSION FROM PHOSPHOGYPSUM STACKS

Location	Mean Ra-226 concentration in phosphogypsum (Bq/g)	Mean radon flux ($Bq \cdot m^{-2} \cdot s^{-1}$)	Radon flux per unit Ra-226 concentration ($Bq \cdot m^{-2} \cdot s^{-1}$ per Bq/g)
Central Florida, USA [150, 151]:			
Stack, side slopes, access roads[a]	1	1	1
Intermittently ponded areas	1	0.075	0.075
South-western Spain [159]:			
Undisturbed surface	0.73	0.01–0.16	0.014–0.22
Surface disturbed by tilling	0.73	0.04–0.3	0.055–0.41
Agricultural soil (for comparison)	0.035	0.003–0.011	0.086–0.31

[a] The individual mean radon fluxes from the stack, side slopes and access roads were similar.

these results indicate that dust inhalation on a restored phosphogypsum stack does not result in significant exposure.

Several studies have been performed to determine the dose received by workers engaged in phosphogypsum stacking operations. The gamma doses received by maintenance workers on stacks in Spain were 0.25–0.35 mSv/a, assuming 2000 h of occupancy, which is quite conservative [157]. In this context, it is worth mentioning that workers perform a variable but significant fraction of their work inside trucks and other machinery which act as shielding against gamma radiation, implying even lower doses in practice.

10.5. USE OF PHOSPHOGYPSUM

10.5.1. Agriculture

Phosphogypsum is used in agriculture throughout the world [33], for example in Australia, Bangladesh, Brazil, Egypt, India, Kazakhstan [136], Pakistan, Spain [161], the Syrian Arab Republic and the USA [162]. In Brazil, 40% of all phosphogypsum produced is used in agricultural applications. In California, USA, a stack of phosphogypsum originating from phosphate rock from Idaho and Wyoming was utilized completely for agricultural purposes, prior to such use being restricted by regulations in 1989. A very small quantity of phosphogypsum with a low radium content produced in Florida, USA (representing only 0.03% of total

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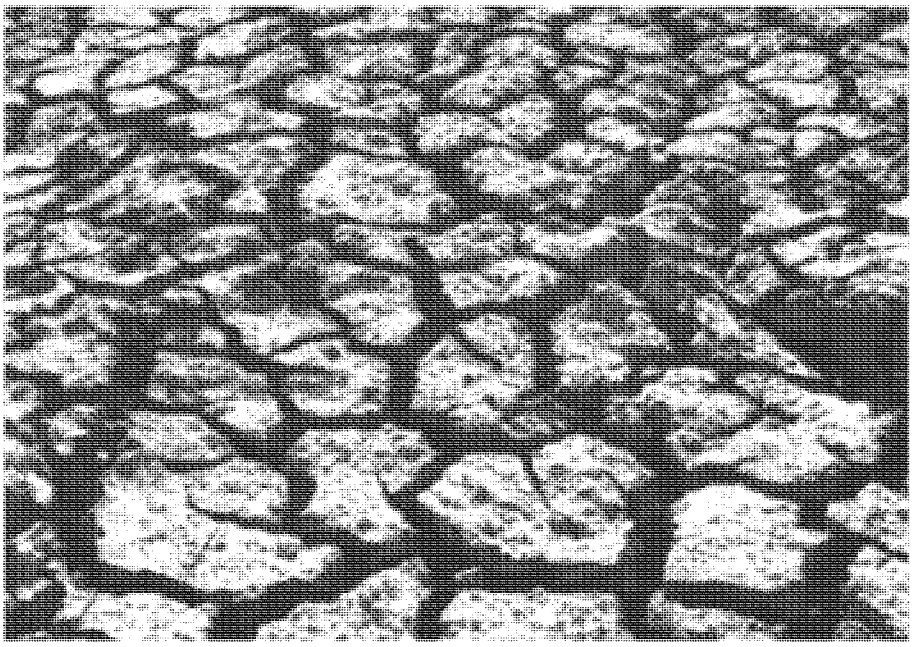

FIG. 44. Soil near Huelva, Spain, prior to remediation with phosphogypsum (courtesy: University of Seville, Spain).

Florida production), continues to be used as a soil amendment in peanut farming. In the European Union, phosphogypsum is permitted for use as a soil amendment under the category 'calcium sulphate' [163, 164]. Phosphogypsum contributes to agricultural production in four principal ways:

(i) Reclamation of land such as estuarine marsh in order to render it agriculturally productive;
(ii) Remediation of saline and sodic soils (see Fig. 44);
(iii) Amendment of soil to prevent crusting and to enhance water retention;
(iv) Fertilization of soil for growing crops and pasture.

Phosphogypsum usually does not need to be tilled into the soil. Freshly generated phosphogypsum is unweathered and moist, and in this state it can be applied directly to the surface of the soil using conventional methods of distribution (see Fig. 45).

A large area of land near Huelva, Spain, has been progressively reclaimed by the application of phosphogypsum and returned to productive agricultural use. An aerial view of the reclaimed land is shown in Fig. 46. This site is particularly

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FIG. 45. Direct application of phosphogypsum to soil (courtesy: University of Seville, Spain).

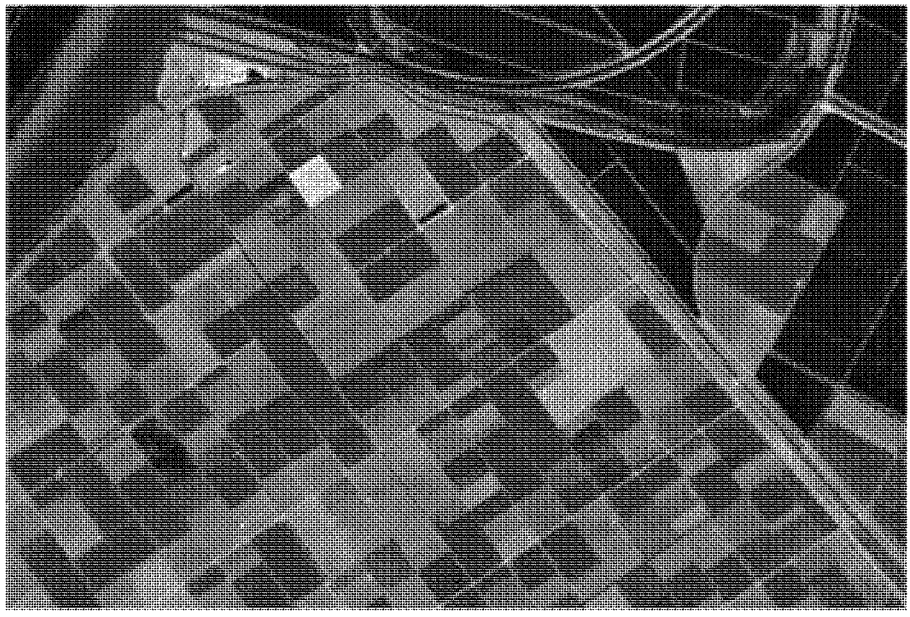

FIG. 46. Land reclaimed by the use of phosphogypsum (courtesy: University of Seville, Spain).

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significant in terms of risk assessment since it is the only documented area in the world which can be used to study the impact of 40 years of continuous use of phosphogypsum on soils, a practice that still continues at this locality.

The benefits of applying phosphogypsum to saline and sodic soils are described in Refs [136, 161, 162] and include:

(a) Reduced sodium and aluminium toxicity of the soil;
(b) Increased calcium and sulphur dissolved from the phosphogypsum;
(c) Increased ammonia retention by the soil;
(d) Increased water retention of the soil through better conditioning;
(e) Greater water efficiency.

The use of phosphogypsum as a fertilizer, typically at application rates of 100–600 kg/ha, has been found to increase significantly the production rates of the following crops [33]:

Alfalfa	Carrots	Lemons	Peaches	Sugar beet
Apples	Citrus	Lentil	Peanuts	Sugar cane
Avocado	Coffee	Limes	Pepper	Sweet sorghum
Bahia grass	Corn	Lucerne	Pineapple	Tea
Barley	Cotton	Maize	Rapeseed	Tobacco
Beans	Cover crops	Mustard	Rice	Tomato
Beets	Forage	Niger	Rye grass	Turnip
Bermuda grass	Frasier fir	Onion	Sorghum	Upland rice
Black gram	Groundnuts	Oranges	Soya beans	Vegetables
Cabbage	Guinea grass	Pasture grass	Squash	Wheat

Phosphogypsum is often used in its unmodified state. Depending on the specific crop application, however, it may be necessary to remove the acidic water (and even some of the other impurities) contained within it. For example, phosphogypsum 'harvested' for agricultural use from the inactive portion of a stack in northern Florida, USA, is first exposed to rainwater for about a year. When the rainwater permeates the phosphogypsum, the acidic process water contained in the phosphogypsum is displaced, causing the pH of the harvested phosphogypsum to increase to a value greater than 5. In general, any removal of impurities has to be kept to a minimum to avoid making the use of phosphogypsum uneconomic compared with the use of relatively inexpensive natural gypsum.

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The use of phosphogypsum as a soil amendment has been studied extensively to determine the extent to which the introduction of additional heavy metals and radionuclides through the application of the phosphogypsum could lead to possible human health effects via the following pathways:

(a) Uptake of radioactivity and heavy metals from the amended soil by edible crops;
(b) Inhalation of radionuclides in airborne dust during the application of the phosphogypsum;
(c) External exposure rates due to the amended soil;
(d) Groundwater contamination;
(e) Radon emission from the amended soil.

In an evaluation of the application of phosphogypsum as a soil amendment and fertilizer [165], phosphogypsum with a ^{226}Ra activity concentration of about 1 Bq/g was assumed to have been applied to the soil every second year for 100 years after an initial application of twice the biennial application rate. Six scenarios were considered, involving various rates of phosphogypsum application in the range 1.66–10 t/ha and tillage depths of 22–46 cm. After the 100 year period, ^{226}Ra concentrations in the soil were calculated to be 0.03–0.12 Bq/g.

An investigation was carried out to determine the effect of phosphogypsum, when used as a calcium fertilizer for the production of crops such as cotton, on the resulting levels and behaviour of radionuclides [166]. Phosphogypsum with a ^{226}Ra activity concentration of 0.51 Bq/g was applied at rates of 13 and 26 t/ha in conjunction with manure at a rate of 30 t/ha. The concentrations of ^{226}Ra in the water draining from the fertilized areas were similar to those reported for non-treated areas (2.6–7.2 mBq/L).[22] The results revealed that the activity concentrations of ^{226}Ra in the crops were not affected by the phosphogypsum treatment and that there was no accumulation of radioactivity in the soil. Similar studies to investigate the buildup of radioactivity in soil or uptake by crops show no significant uptake in most cases [167, 168]. In a study carried out in five land parcels of the central Florida phosphate district, approximately 70 indidividual

[22] While the ^{226}Ra concentrations in the drainage water were not found to be elevated, the concentration of ^{238}U was found to be 200 mBq/L; an order of magnitude higher than normal. However, the ^{234}U:^{238}U isotopic ratio in the uranium-enriched drainage water was 1.16, as opposed to a ratio of 1 in the phosphogypsum and other phosphorus fertilizers used, from which it was concluded that most of the additional uranium in the drainage water did not originate from the phosphogypsum but was thought to originate instead from the uranium naturally present in the soil (at a ^{238}U activity concentration of 0.025 Bq/g) that had become desorbed.

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FIG. 47. Greenhouse studies involving various crops (courtesy: University of Seville, Spain) [170].

food samples were collected and analysed for ^{226}Ra, ^{210}Pb and ^{210}Po [62, 63]. Concentrations of ^{226}Ra and ^{210}Pb in food grown on mined phosphate lands were statistically higher than the concentrations of these nuclides in foods from unmined lands. However, an upper estimate of the likely incremental increase in annual ingestion dose was only 0.027 mSv. A radiological impact assessment of the application of phosphogypsum in agriculture was reported from Greece [169]. The concentration of ^{226}Ra in rice and other agricultural products produced from soil tilled with phosphogypsum ranged from 0.0004 to 0.002 Bq/g and the estimated ingestion dose was 0.86 μSv/a.

A completely randomized greenhouse experiment was carried out in Spain growing tomato (*Lycopersicum esculentum* Mill L.) using a reclaimed marsh soil amended with various rates of phosphogypsum up to 20 t/ha to investigate the transfer of ^{238}U, ^{226}Ra, ^{210}Po, Pb and Cd to the crop [170]. The experimental set-up is shown in Fig. 47. The concentrations of ^{238}U and ^{226}Ra in the crops were below the detection limit in all cases and the concentration of ^{210}Po was 0.0004–0.0007 Bq/g on a dry weight basis. The results also showed that the

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application of phosphogypsum as a calcium amendment for agricultural purposes could lead to some uptake of cadmium in the plants.

In the Cerrado region of Brazil, where significant amounts of phosphogypsum are used for agricultural purposes, a field study explored the impact on two typical soils of the region, one clayey and the other sandy. These analyses included an evaluation of the mineralogical composition, the organic matter content and the concentrations of P, K, Ca, Mg and Al. The concentrations of radionuclides and metals in the phosphogypsum and soil samples were also measured. The organic matter content of the soil samples was low and the potential acidity high. The mean ^{226}Ra activity concentration in the phosphogypsum samples was 0.252 Bq/g. In addition, this study verified that the concentrations of radionuclides and metals in the phosphogypsum were lower than the background concentration in the clayey oxisol soils of Sete Lagoas, Minas Gerais, Brazil. These results indicated that the application of phosphogypsum as a soil amendment in agriculture would not have a significant impact on the environment [171].

A three year field study in Florida, USA, involving the application of phosphogypsum at relatively low rates (up to 4 t/ha), showed no statistically significant increases in radionuclide concentrations in soils and groundwater or in the levels of airborne radon and gamma radiation measured 1 m above the plots [172]. A subsequent study, which has become a benchmark because of its comprehensive methodology and scope [173], developed data to assist in the assessment of the environmental impacts of the application of phosphogypsum at higher rates (up to 20 t/ha) to an established bahia grass pasture, primarily in terms of the radionuclides in phosphogypsum and secondarily in terms of the heavy metal impurities. The results can be summarized as follows:

(a) Exposure from the inhalation of radon progeny was determined from measurements of the ^{226}Ra activity concentration in the soil, the radon flux from the soil and the radon concentrations in the air. For the application of phosphogypsum at a rate of 0.4 t/ha over a 100 year period, the incremental radon flux from the amended soil was projected to be about 40% of the mean value for undisturbed land (with no phosphate mineralization) in the region. For a house constructed on the amended soil, the phosphogypsum in the soil was estimated to increase the indoor radon concentration by about 1–10 Bq/m^3 (representing, for a typical house, an increase of about 2–20%). For a cumulative treatment of up to 40 t/ha, the phosphogypsum was predicted to contribute less than 3.7 Bq/m^3 to the radon concentration over the field.

(b) Exposure to external gamma radiation was determined from dose rate measurements made following a single treatment of phosphosgypsum of up

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to 40 t/ha. After the first year, no gamma exposure attributable to the phosphogypsum could be detected. It was concluded that the radionuclides from the phosphogypsum had penetrated the soil or had been removed by weathering or harvesting. The incremental annual effective dose received by an individual remaining permanently on the treated land was projected to be 0.028 mSv after 100 years.

(c) Exposure from the ingestion of radionuclides in water and food was determined from measurements of the activity concentrations of ^{226}Ra, ^{210}Pb and ^{210}Po in samples of soil, water and forage. The results suggested that the radionuclides contained in the phosphogypsum had limited mobility in surface water and groundwater during the first two years after application to the soil. However, it is possible that they may have been gradually mobilized, appearing in the groundwater at a later date. The activity concentrations of ^{226}Ra in shallow groundwater after 100 years of phosphogypsum use were projected to be about 0.1 Bq/L. Levels of ^{210}Pb were projected to be similar to the baseline levels in runoff and shallow groundwater (<0.04 Bq/L). Doses to humans from the ingestion of animal products that had been contaminated with radionuclides taken up by forage appeared to be within the range of variation in a normal diet.

10.5.2. Construction of buildings

Phosphogypsum has been used as a raw material for cement [174, 175] and as a source of plasterboard. Other construction uses include the production of bricks [176], blocks [177], tiles, artificial stone and even boats [178]. Countries using phosphogypsum for building purposes, usually with certain restrictions, include Belgium, Brazil and India. Phosphogypsum is viewed as a potential building material in South Africa, where the construction of low cost housing is being encouraged. Almost all the uses of phosphogypsum for building products require the phosphogypsum to be well washed to remove the acidity from its residual water content and in some cases further processed to remove residual phosphate.

Recent developments in the phosphate industry in countries with rapidly expanding economies, such as China, have led to a major increase in the production of phosphogypsum, which in turn has stimulated interest in its use, including its use in construction applications [179–182]. As a result, the relevant authorities have taken a greater interest in establishing the necessary conditions for the safe use of phosphogypsum [183, 184]. Exposure to building materials incorporating phosphogypsum has been comprehensively and continuously studied [185, 186]. Exposure levels have been found to depend strongly on exactly how the phosphogypsum is used — exposure from phosphogypsum

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panels, for instance, depends on parameters such as panel design, thickness and density. While most studies show that exposure levels are not likely to be of serious concern, experience suggests that the use of phosphogypsum in building materials is not being given the attention that it perhaps deserves. Attention is often diverted too readily to other, more widely established uses of phosphogypsum such as agricultural applications. This situation appears to have been brought about by two factors in particular:

(i) Compliance with local legal criteria is often raised as an obstacle, often leading to potential uses of phosphogypsum in building materials being dismissed without consideration of the possibility that the criteria themselves might be inappropriate. Ideally, the establishment of criteria for the use of phosphogypsum would be based on empirical scientific evidence relevant to the local situation and would take account of prevailing economic and social factors. Not surprisingly, perhaps, the criteria tend to be based, instead, on a more simplistic approach using theoretical modelling, which is likely to be generic, conservative and limited to purely radiological considerations. Consequently, the criteria end up being unnecessarily restrictive.
(ii) All too often, the use of phosphogypsum is considered only on its direct technical and economic merits as a substitute for other building materials such as natural gypsum (which, in many countries, is in good supply at a competitive price). The broader, less direct benefits of using phosphogypsum in building materials, particularly the additional opportunity that it offers for reducing the financial and environmental liabilities associated with the indefinite storage of phosphogypsum, are not taken into consideration.

Phosphogypsum has also been used in some countries in civil construction applications other than buildings and roads. For instance, the phosphogypsum produced by the largest wet process phosphoric acid plant in China has been used for civil engineering projects such as the construction of the Three Gorges Dam [33], which accounts for nearly 80% of the annual production from the plant.

10.5.2.1. Phosphogypsum in cement

The use of phosphogypsum in cement and related products such as plaster provides an opportunity for consuming large volumes of material. Various options have been pursued in several countries [187–189]. In Europe, the use of phosphogypsum in this manner was well established from the 1960s onwards. In

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former phosphogypsum producing countries such as Belgium and France, the opportunities for significant commercial benefit from the use of phosphogypsum in cement and plaster led to investigations being focused on these applications rather than on other construction applications such as road construction [190].

In Spain, activity concentration measurements were made on two types of cement containing phosphogypsum [185]. The results of the measurements are given in Table 34 — the phosphogypsum used in this application is identified as PG-1 and PG-2. The activity concentrations of ^{226}Ra, ^{210}Pb and ^{210}Po in the cement were much lower than those in the phosphogypsum. The activity concentrations of ^{40}K were higher, while the activity concentrations of ^{232}Th were similar. The significant dilution of activity content indicates the potential for use of phosphogypsum in building materials. Detailed information based on dose assessments can be used to determine further the applications of phosphogypsum as an additive to cement for building applications on a case-by-case basis.

10.5.2.2. Phosphogypsum panels

In a study conducted in Brazil [191–193], exposure levels were measured inside an experimental house constructed using relatively thin, high strength phosphogypsum panels. The walls were composed of double sets of joined panels with a thickness of 1.5 cm and a 15 cm gap between two such joined panels. For ceiling panels the thickness was 1 cm. The house is shown in Fig. 48. The mean radionuclide activity concentrations in the phosphogypsum panel material from three production locations were 0.02–0.39 Bq/g for ^{226}Ra, 0.03–0.85 Bq/g for ^{210}Pb, 0.03–0.25 Bq/g for ^{232}Th and <0.08 Bq/g for ^{40}K. For various realistic scenarios involving the exposure of a house occupant, the projected average incremental dose was found to be 0.02–0.20 mSv/a, with the range of values

TABLE 34. ACTIVITY CONCENTRATIONS IN PHOSPHOGYPSUM AND IN CEMENT CONTAINING PHOSPHOGYPSUM

Material	Activity concentration (Bq/g)				
	Ra-226[a]	Pb-210	Po-210	Th-232[a]	K-40
Phosphogypsum PG-1	0.205	0.161	0.214	0.019	—
Phosphogypsum PG-2	0.170	0.165	0.174	0.006	0.013
Cement 1	0.027	<0.056[b]	0.021	0.017	0.730
Cement 2	0.027	<0.036[b]	0.025	0.013	0.613

[a] The activity concentrations of Ra-226 and Th-232 were determined by equating them to the measured values of Bi-214 and Ac-228, respectively.

[b] Detection limit.

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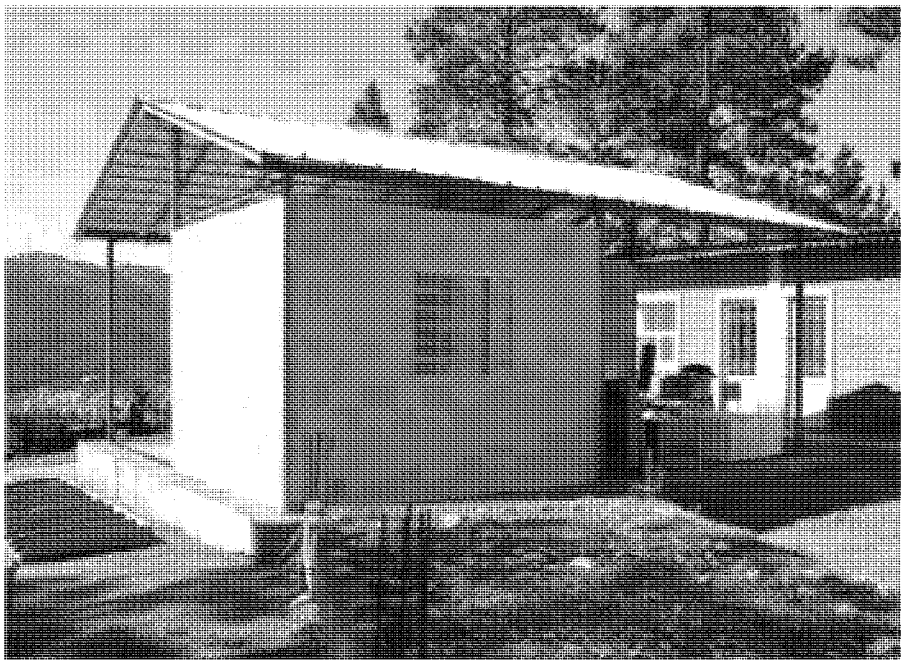

FIG. 48. An experimental house constructed using phosphogypsum.

reflecting the different origins of the phosphogypsum. The radon concentrations measured in the experimental house were found to be 45–119 Bq/m^3, averaged over a period of 15 months, changing detectors every three months. No information on the ventilation conditions in the experimental house was available. However, on the basis of the available data, radon could possibly be an exposure pathway in buildings constructed using phosphogypsum with high radium concentrations.

The use of phosphogypsum plasterboard panels in house construction has also been studied in Australia [194, 195]. The annual effective dose received by the occupant of a room of dimensions 5 m × 5 m × 3 m was calculated, assuming that the walls and ceiling were lined with 1 cm thick phosphogypsum panels having a ^{226}Ra activity concentration of 0.4 Bq/g. The annual effective dose attributable to the phosphogypsum was 0.13 mSv, representing an increment over that for normal construction of 14%. On the basis of measurements made on the panels to determine their ^{226}Ra content and ^{222}Rn exhalation rate, exposure to radon progeny was calculated by modelling a typical building configuration. The measured ^{222}Rn exhalation rates in the untreated plasterboard were in the range 0.0005–0.001 Bq·m^{-2}·s^{-1}. For air exchange rates greater than 0.5 and up to 5 air changes per hour, the incremental annual effective dose from radon progeny

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inhalation was found to be between 0.02 and 0.16 mSv for the maximum measured radon exhalation rate. It was also found that the radon exposure was reduced if the surfaces of the panels were coated with paint or cardboard. Exposure was also reduced by 15–20% if the very fine particles were removed from the phosphogypsum prior to manufacture of the plasterboard. The annual effective dose received via the inhalation of airborne dust by a worker installing the plasterboard was also determined, based on certain assumptions. For particles with an AMAD of 5 μm and having an initial source concentration of 0.4 Bq/g ^{238}U and progeny in equilibrium and a dust concentration of 1 mg/m^3, the inhalation dose was estimated to be 0.05 mSv for an exposure period of 2000 h.

The use of phosphogypsum in building and construction materials has also been investigated in India [196]. Measurements carried out inside a plasterboard plant showed absorbed dose rates in the range 0.03–0.04 μGy/h in the phosphogypsum mixer, aligner, tensioner and hammer mill areas. Higher absorbed dose rates up to 0.1 μGy/h were measured in the product storage area. The mean radionuclide activity concentrations in the 1.25 cm thick plasterboard sheet were 0.09 Bq/g for ^{226}Ra, 0.009 Bq/g for ^{238}U, 0.005 Bq/g for ^{232}Th and 0.015 Bq/g for ^{40}K. Various exposure scenarios were postulated and a dose estimation for each of these scenarios was carried out using methodologies reported elsewhere for the assessment of radiation exposures from building materials containing radionuclides. The maximum doses estimated for the use of phosphogypsum panels in ceilings, walls and floors were in the range 0.15–0.46 mSv/a. Exposure to radon exhaled from the material was not considered, as it was not a significant exposure pathway under the prevailing ventilation conditions. In formulating a regulatory guideline, glass fibre reinforced phosphogypsum panels having dimensions of 12 m × 3 m × 1.25 cm with 48 hollow cavities were evaluated for likely exposures and indicated doses as high as 4.5 mSv/a. However, by restricting the ^{226}Ra concentration in the phosphogypsum to below 1 Bq/g and by applying a surface activity concentration limit of 40 kBq/m^2, the dose could be limited to 0.3 mSv/a. The regulatory guidance also suggested mixing with other ingredients such that the ^{226}Ra concentration in the bulk material is less than 1 Bq/g.

10.5.2.3. Phosphogypsum in glass and glass ceramics

Glass and glass ceramics can be readily manufactured from phosphogypsum and tailings sand [197–201]. Since the materials are vitrified, they exhibit low radon emanation fractions. Products include:

(a) Glass ceramic floor, wall and roof tiles;
(b) Synthetic wollastonite ($CaSiO_3$) fibres used in ceramics and paints and as a non-toxic substitute for asbestos;

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(c) Synthetic stone for building facades;
(d) Abrasives;
(e) Flat 'privacy' glass;
(f) Container glass for selected beverages and agricultural products.

An assessment of doses received by a house occupant as a result of gamma radiation from the use of phosphogypsum in tiles is reported in Ref. [197]. In a typical exposure scenario, the tiles were assumed to be used on the floors of the kitchen, bathroom and entrance hall and on the walls of the bathroom, with the following dimensions:

(a) Tile thickness: 7.6 mm.
(b) Kitchen floor: 5 m × 5 m.
(c) Bathroom and entrance hall floors: 3 m × 3 m.
(d) Bathroom walls: 2 m × 3 m.

The distance from the source was assumed to be 1 m for floor tiles (or 0.2 m for a child) and 0.5 m for wall tiles. The results of the dose assessment for this typical exposure scenario are given in Table 35. Results for what is considered to be an extreme exposure scenario, involving a longer annual exposure period associated with a single 10 m × 10 m room having 7.6 mm thick floor tiles and 10 mm thick roof tiles (unshielded), are also given in Table 35. The most exposed adult is estimated to receive an annual dose of 0.06 mSv (or 0.29 mSv for the extreme scenario), while the most exposed child receives 0.09 mSv (or 0.46 mSv for the extreme scenario).

The use of phosphogypsum glass ceramic tiles in a house has also been investigated in a modelling study with respect to exposure to radon [197]. The material was assumed to consist of CaO and SiO_2 at a mass ratio of 1:3 and to have a ^{226}Ra activity concentration of 0.88 Bq/g, a density of 2600 kg/m^3 and radon emanation of 0.00021 $Bq \cdot m^{-2} \cdot s^{-1}$. The analysis showed that for a house tiled completely with phosphogypsum tiles, the radon exhalation rate was only 10% of that for normal construction materials.

10.5.3. Construction of roads

One of the more widely studied and tested uses of phosphogypsum in construction is for road building [130, 132, 202]. Unpaved phosphogypsum roads are commonplace at phosphoric acid production facilities, especially on and around phosphogypsum stacks. Initial work on the use of phosphogypsum for the construction of paved roads in Belgium [203, 204] and France [205–208] in the 1970s and 1980s focused on its use in embankments [209, 210] and for road

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TABLE 35. EXPOSURE TO CERAMIC TILES MADE WITH PHOSPHOGYPSUM [197]

Location	Absorbed dose rate (μSv/h)		Annual occupancy period (h)		Annual effective dose (mSv)	
	Adult	Child	Adult	Child	Adult	Child
Typical exposure scenario:						
Kitchen	0.025	0.058	2000	1200	0.05	0.07
Entrance hall	0.016	0.048	65	65	<0.01	<0.01
Bathroom, floor	0.016	0.048	250	250	0.004	0.012
Bathroom, walls	0.024	0.024	250	250	0.006	0.006
Total					0.06	0.09
Extreme exposure scenario:						
Floor	0.040	0.070	4500	5250	0.18	0.37
Roof	0.024	0.017	4500	5250	0.11	0.09
Total					0.29	0.46

stabilization [211]. These efforts came to an end for commercial reasons whereby the phosphogypsum under investigation had a more valuable market outlet in wall boards for buildings than in road construction. While some investigative work on the use of phosphogypsum in embankments continued elsewhere [212], ongoing work became focused on the road bed, where phosphogypsum mixed with 5–7% cement and, in some cases, fly ash emerged as the best option [132]. The construction of pilot roads built in this manner has been successfully carried out in climatic regions with wet–dry cycles, such as in Florida, USA [186, 213], South Africa [214] and in climatic regions with freeze–thaw cycles such as in Finland [215]. Although no further paved roads have been built, research into the optimization of the use of phosphogypsum in road construction has continued [216, 217].

It has been determined that the use of phosphogypsum in road base applications could consume 25 000 t per lane kilometre, which would translate into an annual phosphogypsum consumption of some 140 million t in the USA alone. It has also been determined from the pilot studies carried out that the use of phosphogypsum as a road bed material is no more expensive than the use of more

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traditional materials and may actually be less expensive when the full life cycle cost is considered [214]. In Florida, USA, in areas near large quantities of readily available phosphogypsum, the construction cost was found to be close to one third of the cost of using conventional material. With regard to resource conservation and recycling, the pilot studies indicate a potential virgin resource saving of up to two thirds [215]. The major constraints on the use of phosphogypsum in road construction are economic, cultural and regulatory:

(a) Economic constraints [218]: Owing to transport costs, any bulk material used for road construction needs to be readily available from a source located reasonably near the construction site. For phosphogypsum to be viable as a road construction material, it has been estimated that its source would have to be located no more than 150–200 km from the construction site [219].
(b) Cultural constraints: Road builders seem reluctant to substitute phosphogypsum for conventional road bed materials. To overcome such reluctance, a shift in attitudes towards the use of phosphogypsum would be necessary [132]. It has been suggested that the offer of some initial incentive would eventually change current perceptions concerning the use of phosphogypsum, similar to the way in which perceptions in the cement industry have changed from considering fly ash as a waste to considering it as a valuable resource [132].
(c) Regulatory constraints: Even where the environmental impact is considered acceptable once the road is built, other regulatory constraints may still exist. In the USA, for instance, the use of phosphogypsum for road construction is, in effect, prohibited because authorization cannot be obtained for the transport of the material to the construction site [220].

10.5.3.1. Technical considerations

Phosphogypsum has successfully been used as a binder for base course mixtures. Phosphogypsum based mixtures are more workable than clay based mixtures. Delays due to rain during construction are reduced because the compacted mixture does not absorb significant amounts of water. Shrinkage cracks and swelling, which often negatively affect the performance of clay based road beds, are greatly reduced. The stability of compacted phosphogypsum mixtures is superior to that of clay mixtures [186] and there is evidence that the use of phosphogypsum, if correctly optimized, leads to a progressive strengthening of the road bed over time [214, 215].

In Texas, USA, road bases for city streets, shopping centres, truck terminals, parking lots and loading platforms were successfully constructed using

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cement and fly ash stabilized phosphogypsum and fluorogypsum[23] [221, 222]. This was followed, in 1988–1991, by the construction of several experimental sections of road directed towards establishing materials selection criteria, a suitable mix design rationale and construction procedures to permit stabilized phosphogypsum road bases to be used in Texas [223]. The concepts generated were successfully demonstrated in 1991 when a two lane 100 m test section was constructed using a road base consisting of a 7% cement stabilized phosphogypsum mixture with an unconfined seven day compression strength of 3.1 MPa. A second experimental test section was constructed in 1992 using a road base containing equal proportions of bottom ash (comprising three parts boiler slag to one part cinder ash) and phosphogypsum. Two additional road sections were built in 1993 using phosphogypsum blended with fly ash and cement–fly ash, respectively [132]. After two years, these sections were found to be performing well.

In Florida, USA, two experimental roads were built in 1986–1987 using both dihydrate and hemihydrate forms of phosphogypsum [224, 225]. The results of the evaluations are reported in Refs [226–228]. It was concluded that phosphogypsum, when subjected to optimum mixing and compaction, could be transformed into a solid of high strength that is effective as a binder to stabilize on-site soil. Phosphogypsum and sand mixtures, stabilized with a small amount of cement, possessed a load bearing capacity higher than that of locally mined limestone, which was at that time the material of choice for road bases in the region. It was also demonstrated that the incorporation of phosphogypsum into a cement based mixture for making 'roller compacted concrete' (a form of concrete widely used for road construction) led to improved compaction and strength properties [229]. The road bed described in Ref. [224] is shown in Fig. 49, which shows the condition after 25 years of use. The picture was taken during routine resurfacing. While the phosphogypsum is clearly not mixed in fully with other road bed materials, it has, neverthless, lost none of its load bearing strength. As a result, the only maintenance requirement was a new layer of asphalt.

10.5.3.2. Environmental impact

The dissolution and/or leaching of the road bed mix, especially the phosphogypsum component, and any volume change due to changes in water content and/or chemical reactions were evaluated in terms of their potential environmental impact [228]. Laboratory tests showed that leaching from cement

[23] Fluorogypsum is a residue from the production of hydrofluoric acid.

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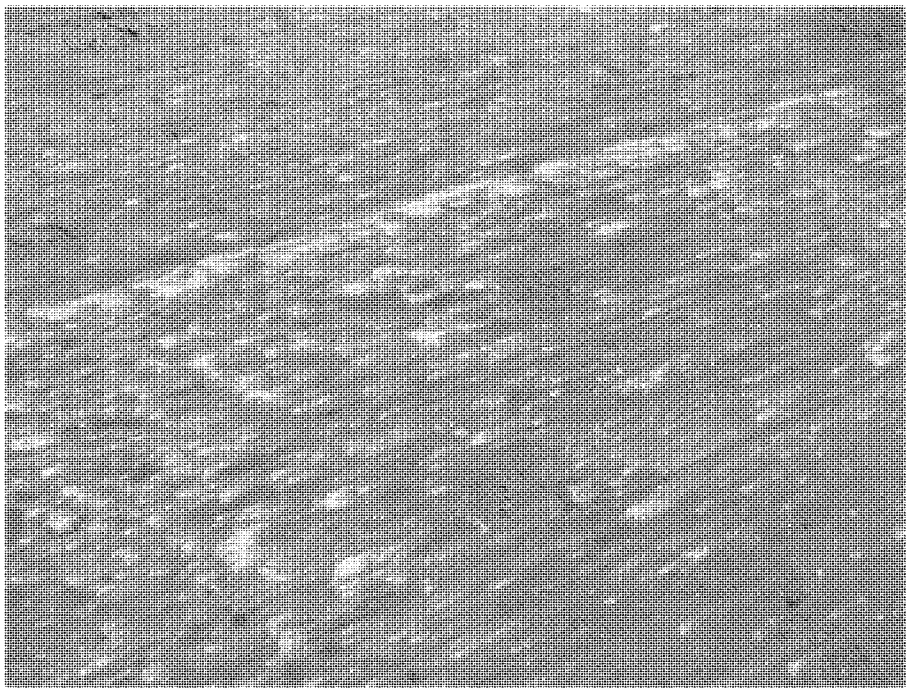

FIG. 49. Experimental road bed in Florida, USA, incorporating phosphogypsum (courtesy: Florida Industrial and Phosphate Research Institute).

stabilized phosphogypsum was below levels of concern, even in the TCLP[24] test designed to simulate the leaching of toxic elements such as mercury and cadmium from material disposed of in a landfill facility. It was found that the leaching of heavy metals into the environment from the phosphogypsum component was lower than that from the cement component. The processes of compaction and cementation were shown to be effective in reducing the leaching of salts. (Compaction also reduced radon exhalation.) It was concluded that no significant leaching of any potentially harmful component of the cement stabilized materials would occur, even where the road base was exposed to free water. The water environment under a road does not change very quickly, since the road bed has a low permeability and the road surface is designed to be impermeable.

The environmental impact of the experimental road bases constructed in Texas, USA, in the early 1990s was evaluated through TCLP analysis of the

[24] TCLP: Toxicity characteristic leaching procedure.

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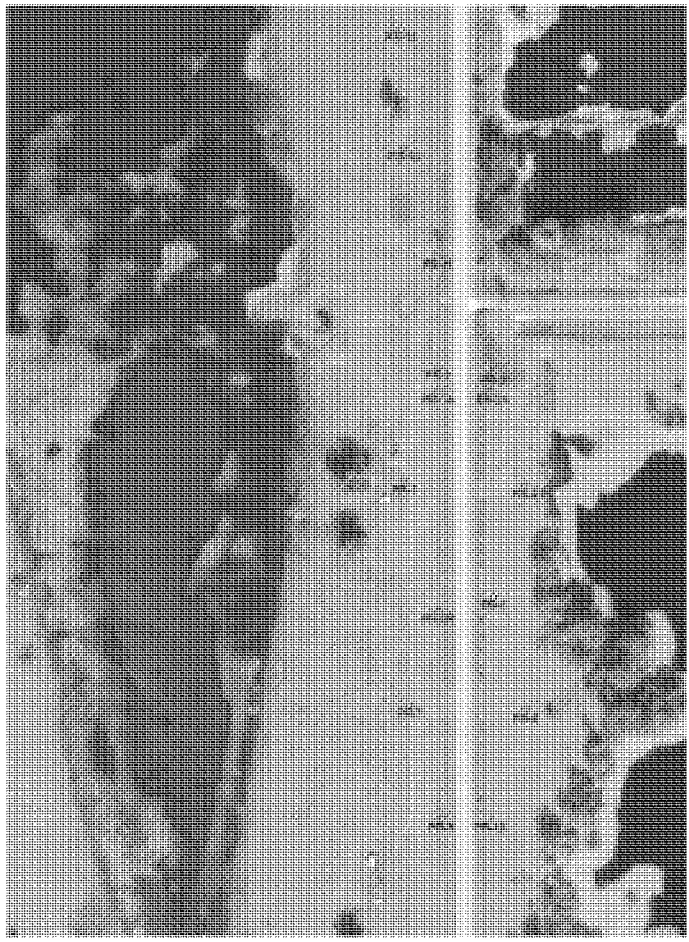

FIG. 50. Aerial view of an experimental road in central Florida, USA, showing the positions of the monitoring wells (courtesy: Florida Industrial and Phosphate Research Institute).

mixture components along with analysis of the groundwater, surface water and leachates [221]. The concentrations of leached chemicals were found to be below levels of environmental concern and in many cases negligible. In central Florida, USA, groundwater monitoring adjacent to one of the two experimental roads constructed in 1986–1987 was undertaken four months prior to construction and thereafter for 27 further months, resulting in a total monitoring period of 31 months [230]. Follow-up monitoring continued until 2008. The positions of the monitoring wells relative to the road are shown in Fig. 50. No significant impact on the groundwater was detected, with the concentrations of leached chemicals all remaining below levels of environmental concern [231].

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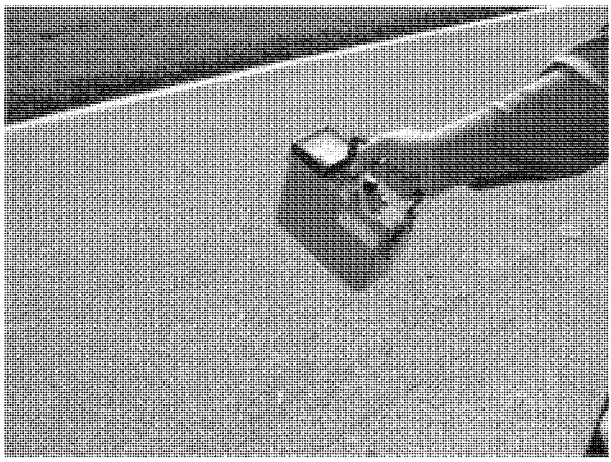

FIG. 51. Monitoring of gamma radiation above an experimental road in Florida, USA (courtesy: Florida Industrial and Phosphate Research Institute).

Groundwater monitoring of the second of the two experimental roads constructed in 1986–1987 was carried out in a similar manner and, again, the experimental road was found to have no measurable impact on the quality of the groundwater.

10.5.3.3. Radiological impact

The two experimental roads constructed in Florida, USA (see Section 10.5.3.1), were subjected to a radiological assessment by monitoring the air, soil and groundwater before and after construction [230]. The monitoring addressed gamma radiation (see Fig. 51), outdoor radon and ^{226}Ra in samples of water and soil. From the results of gamma exposure measurements, it was determined that the absorbed dose rates 1 m above the paved road surface were 0.015–0.035 μGy/h higher than pre-construction values and did not change appreciably over time. These incremental dose rates are within the normal range of variability of background levels. The radon concentrations measured in the air and soil after construction were not significantly different from those measured before construction [232]. The same was found to be the case for the activity concentrations of ^{226}Ra measured in the groundwater (over a one year period) and the soil around the experimental roads. It was concluded, therefore, that the construction of the roads had had no appreciable effect on radon and ^{226}Ra levels in the surrounding environment.

Gamma radiation monitoring was also carried out above an experimental road surface made from roller compacted concrete containing phosphogypsum (described in Section 10.5.3.1) [229]. The absorbed dose rate 1 m above the road

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surface was determined to be 0.009 μGy/h, about 50% lower than that recorded above a nearby asphalt road (0.020 μGy/h) and about 25% lower than that recorded above a nearby non-paved surface (0.012 μGy/h).

10.5.4. Marine applications

Many phosphogypsum stacks are located around low lying coastal areas and the use of this phosphogypsum in marine applications is therefore an attractive proposition from an economic point of view. Marine applications of phosphogypsum offer many potential benefits, including the stabilization of vulnerable coastlines, the protection of areas such as coastal wetlands against the risk of flooding and the re-establishment of coastal industries such as shellfish production.

Research has focused on the stability of mixtures of phosphogypsum, fly ash and cement in seawater environments and their effect on the surrounding marine environment, with particular attention being given to the suitability of such mixtures for making oyster cultch or artificial reefs [233–239]. Mixtures containing various proportions of phosphogypsum (55–73%), cement (2–10%) and fly ash (25–42%) have been found to suffer little degradation in sea water over periods of up to two years. A key factor in creating resistance to degradation in sea water and reducing the diffusion of heavy metals and ^{226}Ra is the formation of a calcite ($CaCO_3$) surface layer that acts as a physical barrier to seawater intrusion. The inclusion of fly ash in the stabilized phosphogypsum mixture promotes the formation of such a layer while limiting the required cement content to only 2–3%. The leaching of heavy metals and ^{226}Ra from stabilized phosphogypsum is comparable with that from pure cement and well below levels that might be of concern for health. Tests in the field have shown that stabilized phosphogypsum mixtures are capable of supporting the growth of oysters and other shellfish and do not lead to any significant bioaccumulation of heavy metals in fish.

10.5.5. Landfill

Phosphogypsum has been shown to have good potential for use as a cover material in landfill disposal facilities [240–242]. In Italy, phosphogypsum has been used experimentally as a liner for landfill on the edge of the Venice lagoon [243]. Laboratory studies and pilot scale testing indicate that the sulphur in the phosphogypsum increases the biological activity in the buried refuse. The increased rate of degradation allows 30–45% more waste to be buried in a given volume of landfill, thus considerably extending the useful life of the facility. Since an industrial landfill facility is designed to isolate the waste from the surrounding environment, for instance through the use of an impervious liner, it is highly unlikely that the additional amounts of heavy metals and ^{226}Ra introduced

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through the phosphogypsum would lead to any significant environmental or radiological impact.

10.5.6. Sulphur recovery

The use of phosphogypsum as a source of sulphur has been studied extensively. Many process routes, both chemical [244–249] and biological [250–252] have been explored, but all require considerable energy inputs. With the availability of low cost by-product sulphur from the oil and gas industry, the recovery of sulphur from phosphogypsum is unlikely to be competitive from a purely economic point of view. However, because of the considerable financial implications associated with the continued storage of phosphogypsum in stacks, the use of phosphogypsum as a source of sulphur could become worthwhile from a broader perspective, particularly since, in the chemical recovery process, the radionuclides in the phosphogypsum appear to migrate to the calcium carbonate by-product, leaving the ammonium sulphate intermediate product free of radioactivity [253]. The radiological aspects of biological recovery processes have not been studied, but it can be expected that the radionuclides would remain in the residue after removal of the sulphur content, leaving the sulphur essentially free of radioactivity.

10.5.7. Other uses

Phosphogypsum has many other uses that have proven to be successful and economic, although the amounts of material involved are generally small. Such uses include:

(a) Treatment of industrial waste:
  (i) Bauxite waste [254];
  (ii) Coal mining waste (removal of barium and radium) [255];
  (iii) Metal finishing waste [256];
  (iv) Textile waste (removal of colour and organics) [257].
(b) Agricultural applications:
  (i) As a binder for fertilizer [258];
  (ii) As an additive to bauxite residue for use in improving phosphorus retention in sandy soil [259].
(c) As an additive for improving the performance of bauxite residue drilling mud [260].
(d) As a filler for 'plastic wood' [261].
(e) As a de-icing additive [262].

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10.6. DISPOSAL OF PHOSPHOGYPSUM

The rate at which phosphogypsum is produced far exceeds the rate at which it is used. In addition, very large stockpiles of phosphogypsum from past production are held in indefinite storage in stacks (see Section 10.1). Unless this phosphogypsum can be put to good use in the foreseeable future, the need for the disposal of large amounts of phosphogypsum will remain. The most common methods of disposal are in situ disposal through stack closure and discharge to water bodies as a dilute slurry. Relatively small amounts of phosphogypsum are also disposed of by backfilling in mined-out areas.

10.6.1. In situ disposal through stack closure

10.6.1.1. Evolution of the approach to closure

The worldwide trend has been for production facilities to become consolidated, resulting in significant increases in production capacity. This has created a tendency to close older, smaller phosphogypsum stacks and to plan for a smaller number of very large ones. As an example, an older type of stack was closed on the edge of Tampa Bay in Florida, USA, in 1992. At the time of closure, the stack covered a land area of 138 ha and its height was 66–69 m. During operation, it was growing in height at a rate of about 6 m per year [263]. Some older stacks were not formally closed, having been abandoned by their owners, and have tended to blend into the landscape over time as a result of local vegetation establishing itself on the stack surface.

Stack closure has become significantly more common in major production centres such as those in Florida, USA, as the industry scales back production or stacks reach their maximum usable height. The closure process in Florida is subject to a formal procedure involving the establishment of detailed specifications and resulting in a published plan, usually subdivided into phases [264, 265]. The Tampa Bay stack closure [263] was completed in just over a year (1992), while a stack at Piney Point required more than two years to close [266].

Although closures of production facilties have become more commonplace since the 1990s, closure of the associated stacks has tended to be carried out in an unplanned or unforeseen way, often as a consequence of the bankruptcy of the producing company. There has been a lack of forward planning, particularly where the closure of production facilities has marked the end of national production capacity. Owing to inadequate communication within and between countries, the lessons learned from stack closure at one site have not been transmitted to other sites. Instead, the approach to stack closure has been ad hoc in nature, resulting in inconsistency between sites and unnecessarily high costs.

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The situation is now changing, however. At some sites, such as that at Huelva, Spain, planned closure is now being pursued actively, leading to the emergence of some best practices that could beneficially be passed on to other sites in due course.

For new production facilities, the adoption of a complete life cycle approach, in which eventual stack closure forms an integral part of the planning of the facility, brings substantial benefits. These include reduced financial and environmental burdens and better prospects for the eventual use of the phosphogypsum, the pond water and the land (thus offsetting the costs of stack closure). One of the many implications of such an approach is that it would put an end to the common practice of burying waste indiscriminately in the stack with no records and, instead, lead to the implementation of a standard operating procedure that designates specific areas for burial with an associated long term management plan. In terms of the life cycle approach, any new facility would have in place, from the outset, a clear plan for stack closure that would be sufficiently detailed to enable the proper financial provision to be included in the planning of the facility as a whole. Lessons learned at facilities such as Gela, Italy, and Piney Point, USA, have shown that the magnitude of this financial provision could be very large. This could have significant implications for countries building production facilities for the first time or which are significantly increasing their current levels of production. The large capital investment required to establish a facility combined with the need to make adequate provision for closure costs could threaten the success of the business enterprise from the outset. This underlines the need for making sensible and well thought out policy and regulatory decisions so that these 'negative externalities' are no greater than they need to be.

10.6.1.2. The closure process

The older the stack, the more likely is the occurrence of problems in the closure process, especially problems related to the very large volumes of process water contained on top of, or within, the stack. Closure activities associated with the stack itself and with the stored process water are interdependent. When the storage capacity of a phosphogypsum stack is exhausted or when a production facility is permanently closed, not only the pond water but also the seepage and rainfall runoff have to be contained within the site and/or treated before discharge. This has to continue for as long as rainwater is able to infiltrate the stack and/or until the water in the pores of the phosphogypsum has drained out. In addition, prolonged rainwater infiltration will produce a network of dissolution cavities that could make it more expensive to cap the stack at a later date.

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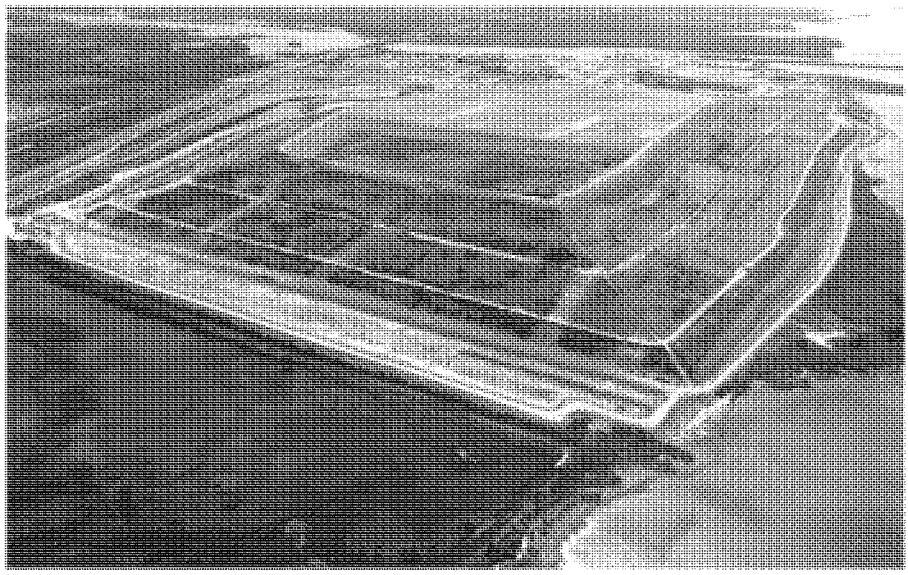

FIG. 52. A computer modified image of the regrading of a stack as part of the closure process (courtesy: Fertiberia, Spain).

Regrading and revegetation of the side slopes, after any necessary surface treatment with dolomitic limestone to rectify magnesium deficiency in the topsoil, may often be sufficient to prevent rainfall (and snow melt) from seeping into the slopes and may thus allow for subsequent runoff to be discharged from the site without treatment. Under favourable climatic conditions and hydrogeological settings, regrading of the top of a gypsum stack to promote surface runoff in combination with good vegetation and/or a relatively impervious clay cover may be sufficient to prevent rainfall infiltration. In other situations, capping with an impervious geosynthetic barrier may be needed. A stack undergoing regrading is shown in Fig. 52.

Revegetation of phosphogypsum stacks is greatly facilitated by the fact that phosphogypsum performs well as a soil. An example of revegetation at a site in Italy is shown in Fig. 53. At this site, stack closure was carried out as part of the total decommissioning of the phosphoric acid production facility — this is possibly the first global example of such an integrated approach to decommissioning and closure. The integrated approach also opens up the possibility of controlling the sequence of activities such that the process equipment in the plant can be used to facilitate stack closure. At the Piney Point facility in Florida, USA, for instance, the cost of stack closure was reduced by redeploying equipment in the phosphoric acid plant to treat the acidic pond water instead.

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FIG. 53. Planned revegetation of a stack at Gela, Italy.

Once infiltration into the stack has been eliminated, the stack will continue to drain until any settling due to consolidation and creep is complete and the moisture in the phosphogypsum pores reaches its maximum retention capacity. Overall, drainage depends on the dimensions and age of the stack, the properties of the phosphogypsum and the hydrogeological setting. A stack constructed on porous ground will drain much more rapidly than one constructed on low permeability clay.

10.6.1.3. Removal of closed stacks

Stack closure is not an irreversible process and it is, therefore, possible for all or part of the phosphogypsum contained within a closed stack to be subsequently retrieved for use. One important consideration in the reopening of a closed stack for this purpose is the presence of other waste materials within the stack that may have significant levels of contamination. One option is for these materials to be reburied within the remnants of the stack. Alternatively, they may be transported to another disposal site.

A stack may also be removed in order to make use of the land on which it stands. The spread of urban development is bringing populated areas ever closer to older stacks, many of which are no longer in operation. Examples of this

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FIG. 54. New housing development next to a phosphogypsum stack at Gela, Italy.

situation can be found in Greece, Italy (see Figs 54 and 55) and Spain (see Fig. 56). In Greece, the city of Athens has actually engulfed a stack associated with a former production facility, with only the surface of the stack itself remaining free of buildings. Owing to the growth in real estate values at many of these sites, there is increasing interest in removing some of these older stacks and remediating the land for development. Developers have indicated an interest in removing a stack at Thessaloniki, Greece, in order to develop the site for residential purposes. A similar situation exists in the Tampa Bay region of Florida, USA, where property developers are seriously evaluating the costs of remediating contaminated sites to enable their use for residential development. Production facilities are often situated in coastal areas that have become increasingly prized by property developers. These sites may offer a good financial return if they can be brought back into consideration for building purposes, especially residential housing. The freeing of land for public use by stack removal has already brought community-wide benefit, as illustrated by examples in Athens, Greece [267], and Sfax, Tunisia [268], where new recreation facilities have been established on the remediated sites. More information on the remediation of a phosphogypsum stack in Tunisia is provided in Annex II.

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FIG. 55. Commercial buildings next to a phosphogypsum stack at Gela, Italy.

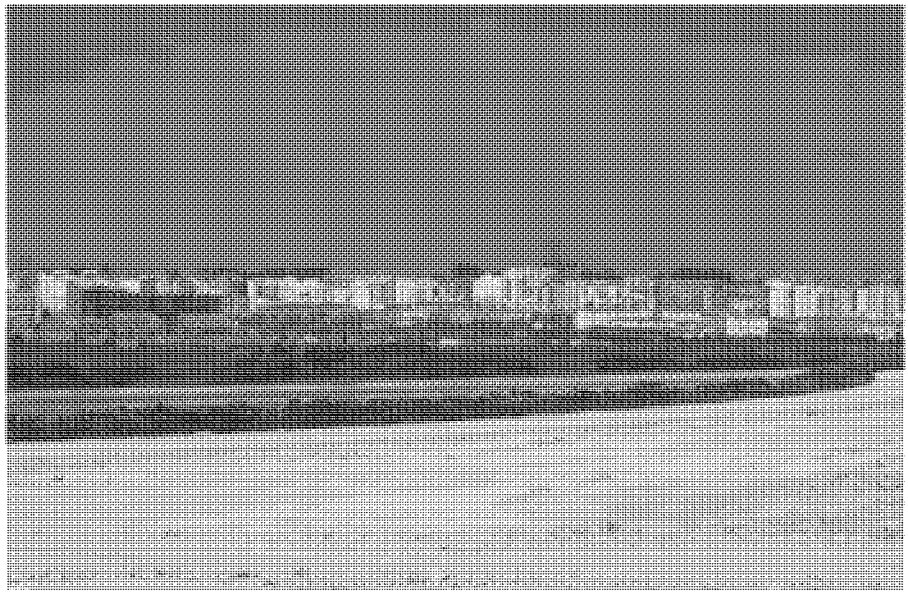

FIG. 56. The edge of a phosphogypsum stack at Huelva, Spain, with the city of Huelva close by.

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10.6.1.4. Radiological aspects

The closure of a stack, when conducted in a planned and effective manner, ensures that any future migration of potential pollutants, such as acidic water, heavy metals and radionuclides, remains at acceptably low levels. Thus, the radiological impact on members of the public living nearby is insignificant. Extensive monitoring carried out over many years at over twenty sites in Florida indicated that radionuclide discharges from stacks and migration to groundwater are insignificant [81]. Operating experience also suggests that doses to the public from legacy sites are negligible. Many older stacks that have already been closed are legacies of former production operations and may not have been closed in accordance with current standards. In such cases, the radiological (and non-radiological) impacts may be greater than those considered acceptable in terms of current standards. Where this is found to be the case, a decision on possible remediation (or removal) would have to be taken by the relevant national authority, bearing in mind that the costs involved could be very high.

10.6.2. Discharge to water bodies

It has been estimated that, up to 2006, a worldwide total of 1.8–3.0 billion t of phosphogypsum had been disposed of by discharge to water bodies, representing 29–50% of all phosphogypsum produced up to that time (see Table 32). This form of disposal was at one time practised widely in Europe. However, as a result of the progressive imposition of legal restrictions on this form of disposal, most phosphoric acid production in Europe (and thus the discharge of phosphogypsum) has now ceased. The situation in the USA and China has been much the same. Discharges to water bodies are currently running at about 31 million t per year, representing 19% of the total amount of phosphogypsum produced annually worldwide. All of these discharges occur in countries outside Europe and the USA, where, on average, they account for about 30% of those countries' current phosphogypsum production. Further information on discharges of phosphogypsum to water bodies is given in Table 36.

The discharge of phosphogypsum as a dilute slurry to the sea has been practised on a large scale by phosphoric acid production facilities situated at coastal locations. In principle, given appropriate conditions in the receiving waterbody, the environmental impact of this form of disposal is apparently negligible. Such conditions were not considered to prevail in the case of discharges to water bodies such as the Irish Sea, the North Sea and parts of the Mediterranean, however, and such discharges have now ceased [269]. For example, discharges into the North Sea from a phosphoric acid facility at Sellafield, UK, were found to have led to the uptake of radionuclides by marine

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TABLE 36. DISCHARGE OF PHOSPHOGYPSUM TO WATER BODIES, BY COUNTRY

Country	Status of discharges
Canada	Former discharges to the bay and inland sea have now ceased.
China	25% of phosphogypsum was discharged to rivers. Discharges have now ceased.
France	Significant discharge to the river in the past and now ceased.
Lebanon	Discharges to the sea.
Morocco	All phosphogypsum is discharged to the sea. The policy for future discharges is under review.
Netherlands	All phosphogypsum was discharged to estuaries. Discharges ceased in 2001 owing to the closure of the plant because of the costs of regulatory compliance.
South Africa	Significant discharge of phosphogypsum to the sea.
Spain	20% of phosphogypsum was discharged to a river estuary. Discharges ceased in 1988.
Tunisia	Progressive termination of discharges to the sea. Discharges planned to cease entirely in 2012.
UK	All phosphogypsum was discharged to the sea. Discharges ceased in 1992, largely because of the costs of regulatory compliance.
USA	An estimated 23% of the phosphogypsum produced up to 1981 (500 million t) was discharged to rivers and to the sea. Discharges ceased in 1982.

food sources [86]. In the light of experience such as this, and because of heightened sensitivities about pollution of the marine environment in general, the discharge of phosphogypsum to the sea is widely regarded as environmentally unacceptable and in contravention of international agreements. In most countries, legislation now prohibits such discharges and the resulting financial consequences have caused many facilities to close down. As a result of these developments, discharges of phosphogypsum to the sea have, since the 1990s, been progressively curtailed [33].

A similar situation exists for discharges to other large water bodies. Discharges to major rivers such as the Yangtse in China or the Mississipi in the USA[25], as well as to estuarine environments such as that at Huelva, Spain, have ceased. Follow-up studies based on field measurements made at Huelva have indicated that, once the discharge ceases, the self-cleaning properties of flowing

[25] A phosphoric acid production facility near Taft, Louisiana, discharged phosphogypsum directly into the Mississippi River from the 1960s to the mid-1980s.

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or tidal waters can be expected to reverse the buildup of contamination back to natural background levels [270–272]. The situation at Huelva is, however, influenced by the presence of an operational phosphogypsum stack that potentially acts as an ongoing source of contamination of the estuary. The evidence suggests that, because of this, the contamination levels in the estuary, while reducing gradually, may remain elevated above background levels for some time [273]. In a study carried out by the European Commission on radionuclide discharge from the phosphate industry to north European marine waters [269], estimated discharges of 65 TBq of ^{226}Ra and ^{210}Po, together and 32 TBq of ^{210}Pb, were reported for a period of more than two decades of operation. Analysis of several marine species indicated increased accumulation of ^{210}Po, possibly attributable to discharges. Probably as a result of closure of some of the industries and technological improvements in existing processing plants, a downward trend in activity discharges was noted.

10.6.3. Backfilling into mined out areas

The pits created by the mining of phosphate ore may, in some instances, be remediated by backfilling with a blend of clay tailings from the beneficiation process and phosphogypsum obtained directly from the filtration system of the phosphoric acid plant. The high calcareous content of the clay neutralizes the acid retained within the phosphogypsum. Such an approach has been adopted at a facility in North Carolina, USA, where a unique set of hydrogeological conditions favour this method of disposal.

10.7. REGULATORY CONSIDERATIONS

The storage of phosphogypsum in stacks, irrespective of its radioactivity content, creates potential environmental and physical safety hazards and, therefore, needs to be controlled by the relevant authorities in a consistent and harmonized manner. Similar controls are necessary when a stack is undergoing closure. Evidence shows that, with such controls in place, there is no necessity for additional regulation for purely radiological purposes. Future liabilities associated with the continued presence of large phosphogypsum stacks place a considerable burden on future generations. This, together with the increasing rate of phosphogypsum production, provides a very compelling reason for creating a regulatory environment that is conducive to identifying and promoting further ways of safely using phosphogypsum as a co-product of phosphoric acid production rather than having to manage it as waste.

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For the forseeable future, the discharge of phosphogypsum to water bodies is largely being phased out but is likely to continue in some countries. Experience has shown that, to ensure acceptable levels of risk to humans and to the environment, such discharges would need to be regulated as part of an authorized practice on the basis of a situation specific risk assessment.

All evidence suggests that the doses received as a result of the use of phosphogypsum in agriculture, road construction, marine applications and in landfill facilities are sufficiently low that no restrictions on such uses are necessary. The uses of phosphogypsum in structural panels for the construction of a house could, in extreme circumstances, result in the occupant receiving an annual effective dose exceeding 1 mSv. Therefore, it would be prudent for the relevant authority to ensure that an appropriate situation specific risk assessment be carried out in order to determine whether any restrictions on this particular use of phosphogypsum are needed. For all other uses of phosphogypsum in home construction, including its use in cement, bricks, plasterboard and tiles, the annual effective dose received by the occupant is unlikely to exceed 1 mSv and restrictions on such use would appear to be unnecessary.

11. DECOMMISSIONING OF WET PROCESS PLANTS AND MANAGEMENT OF SCRAP

Given the substantial capital investment needed to construct wet process facilities, the plants are usually operated for very long periods. Some plants have been in continuous use for well over 50 years and have been in a state of continuous maintenance because of corrosion and the formation of scale and sediments. During the course of routine operations, production is suspended for short periods to allow critical items such as pipes and filter cloths to be cleaned or replaced. Thus, scrap materials are generated throughout the life of the plant, as well as during the eventual decommissioning process. With the possible exception of the decontamination of the land on which the facility is situated, the issues addressed during routine maintenance tend to be similar to those addressed during the decommissioning process.

11.1. DECOMMISSIONING

Considerable knowledge and experience is being established in connection with the ongoing decommissioning of wet process plants, notably in Western

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Europe, where production in most countries has ceased. Examples include plants in France, Italy [31], Greece [274], Netherlands [66] and the UK [68], which were forced to close as a result of new legislation that prohibited the discharge of phosphogypsum to water bodies. In order to continue operating, these plants would have been required to store phosphogypsum in stacks, a process that would have been prohibitively costly and in some cases not even possible because there was no available land on which to locate the stacks. Two such plants are shown in Figs 57 and 58. Usually, decommissioning is carried out as part of the permanent closure of the production facility, in which case the decommissioning process covers the decontamination and dismantling of the plant together with the remediation of the site. There are exceptions, however:

(a) While decommissioning typically includes the dismantling of a plant, or part thereof, a facility may be decommissioned without dismantling. In such instances, after decontamination, the existing or modified structure may be put to another use.
(b) Sometimes, an old plant may be decommissioned so that it can be replaced by a new plant on the same site. In such situations, it is now common practice to address issues such as soil contamination as part of the rebuild rather than deferring them to the time of final closure of the facility.

Normally, the decommissioning process is planned as part of the orderly termination of the business. Sometimes, however, the process is unplanned because outside intervention has become necessary following a failure of the business. In such cases, bearing in mind that an abandoned plant deteriorates rapidly, decommissioning may have to be carried out urgently.

11.1.1. Development of the decommissioning plan

The first step in the decommissioning process is the development of a decommissioning plan. This plan sets out the necessary sequence of administrative and technical actions leading to the eventual removal of some or all of the regulatory controls applied to the facility during its operation. The plan also sets out the necessary policies and procedures, which typically include the following:

(a) A health and safety policy, with allocation of roles and responsibilities;
(b) An outline procedure for dismantling the installation, with flowsheet and timeline;

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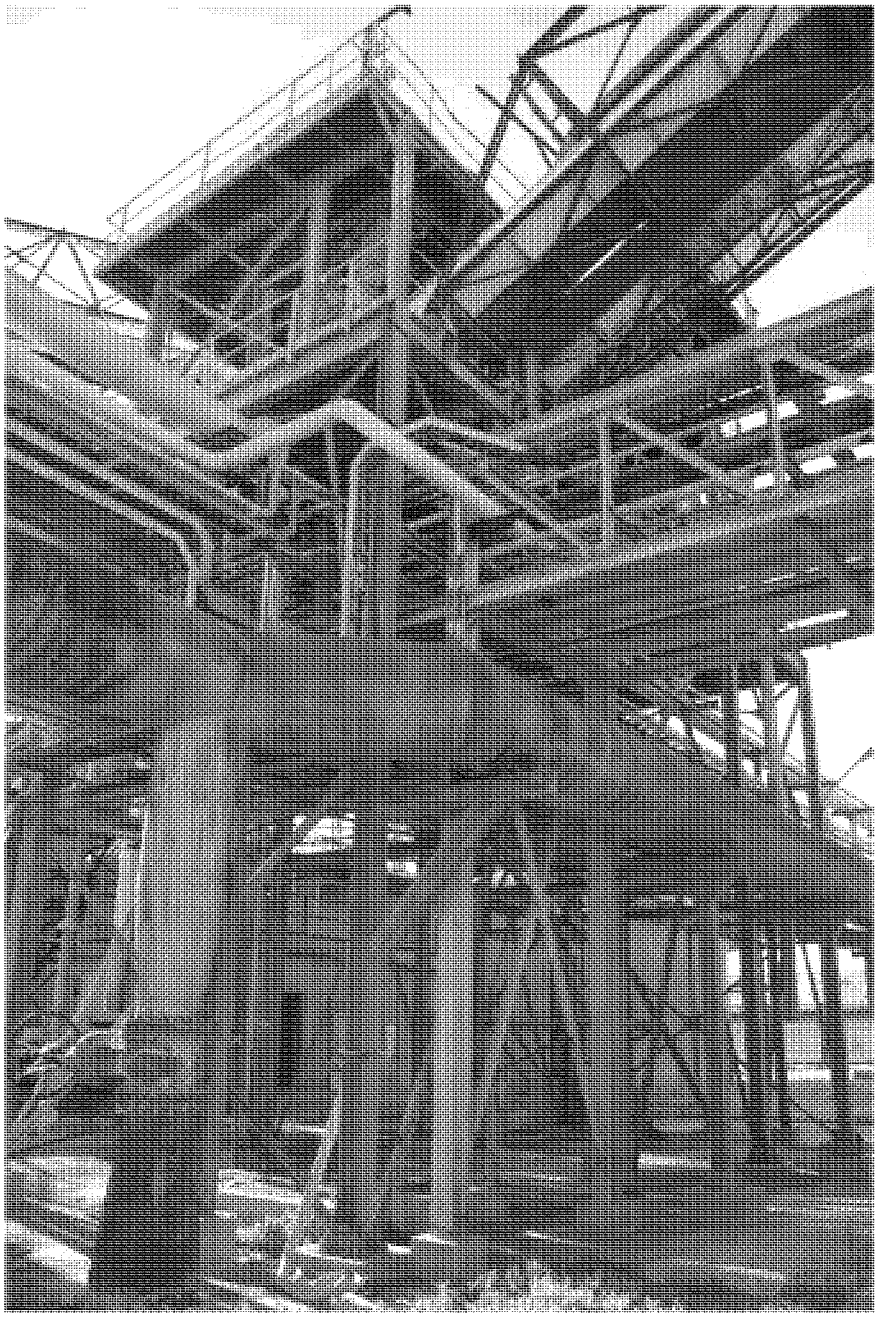

FIG. 57. A deteriorating phosphoric acid plant awaiting dismantling.

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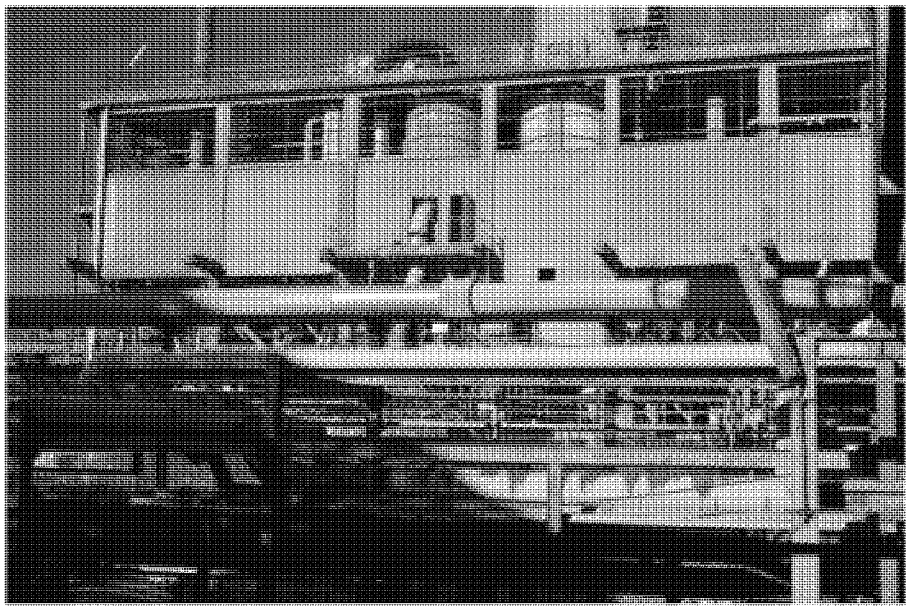

FIG. 58. A wet process plant at Gela, Italy, during decontamination and dismantling.

(c) Procedures for the flushing of process lines, the cleaning of vessels and the categorization of wastes as hazardous, radioactive or mixed;
(d) Standard operating procedures for contractors and third parties, with training and certification requirements as appropriate;
(e) A methodology for the treatment, transport and disposal of scale, other radioactive material and radioactively contaminated equipment, including the necessary documentation;
(f) Contingency arrangements.

The decommissioning plan is based on a comprehensive radiological survey that identifies the location of radioactive material and the resulting exposure levels over the whole site, including peripheral areas used for activities such as transport, cleaning, repair and maintenance. The activity concentrations of radionuclides in environmental media such as water, soil and crops may have to be measured in areas surrounding the site to determine any contamination via airborne dust or entry into water courses. In addition, the survey needs to identify the radiological situation that will prevail during the decommissioning process itself as a result of the presence of radioactive material and contaminated equipment associated with decontamination and waste management activities.

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The decommissioning plan incorporates a detailed description of the facility, including a history of operations at the site compiled from official records and, where appopriate and feasible, from worker interviews. A detailed knowledge of these aspects helps to ensure not only that the radiological objectives of the decommissioning process are achieved but also that the scale and cost of the decommissioning process do not extend beyond what is really necessary. The following historical aspects are typically documented:

(a) All known industrial activities carried out on the site since the land was first occupied and developed;
(b) The process steps in which radioactive material was handled, the locations of the pipes, pumps, valves, tanks and storage areas involved, and the activity concentrations of the materials concerned;
(c) As full a description as possible of plant modifications and changes of ownership;
(d) Known leakages, spillages and movement of radioactive material, including transfers from storage for onward transport and transfers to impoundment areas.

The plan addressses each aspect of the decommissioning process in a level of detail commensurate with the degree of radiological hazard. As a plant undergoing decommissioning is likely to have been in operation for a long time, often with imperfect documentation and record keeping, it can prove difficult to anticipate exactly the location, nature and extent of radioactive deposits and soil contamination that have accumulated over the years of routine plant operation. For this and other reasons, the plan may have to be adjusted in response to unforeseen events as the decommissioning process proceeds.

The decommissioning plan quantifies the likely environmental impacts of the decommissioning process and the risks (both radiological and non-radiological) to workers engaged in the decommissioning work and to members of the public. In this regard, the following process materials are typical of those that have to be considered:

(a) Acids used in the various production processes;
(b) Ammonia;
(c) Hydrogen sulphide that might be present in sulphur storages;
(d) Scale, sludge residues and other materials in which radionuclides, such as radium, and heavy metals, such as arsenic, cadmium, chromium, lead, mercury and selenium, may accumulate.

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The adoption of postulated 'scenarios' can be useful in the planning of a decommissioning process, especially if there are major gaps in the known history of the plant. The scenario concept permits a 'what if' approach to the determination of hazards and risks that may be present at the site. It also facilitates future planning, including the consideration of possible future uses of the site and the likely exposure implications.

The compilation of the necessary risk assessments and other documentation is facilitated by having a comprehensive checklist of all types of equipment on the site, which may typically include:

(a) Reactor vessels, such as the attack tank and defluorination reactor;
(b) Storage tanks;
(c) Buffer tanks for spilled acids;
(d) Evaporators;
(e) Scrubbers;
(f) Pumps, valves and steel pipes, including rubber linings where used;
(g) Stainless steel frames, transport reels and rubber belts from belt filters;
(h) Seal tanks and table filters;
(i) Filter cloths and bag filters;
(j) Metal filter pans;
(k) Machine frames and other metal structures;
(l) Carbon stones and bricks from the reactor lining;
(m) Other bricks and ceramic floor tiles;
(n) Drains, gutters and drain wells.

The decommissioning plan sets out the training and safety procedures to be used, including the keeping of records of the training provided. The responsibility for radiation protection training is generally assigned to a designated radiation protection officer. The training of on-site personnel is of particular significance since few, if any, of these individuals are likely to have had prior experience of working in such an environment. The procedures are usually designed to ensure that work experience is formally documented in order to support a systematic learning process and to ensure that best practices developed during the course of the work are passed on to other decommissioning operations in the future.

11.1.2. Implementation of the decommissioning plan

The decommissioning process is carried out in accordance with the decommissioning plan. An operational survey may be carried out during the process in order to monitor progress and thereby identify any adjustments to the plan that may become necessary.

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Data relating to the dismantling and removal of equipment and the removal of residues, including radiological data such as gamma dose rates and surface contamination levels, are fully documented as the decommissioning process proceeds. The results of the radiological measurements provide the basis for determining how to deal with the materials and equipment and, in particular, whether they meet predetermined clearance criteria and can thus be released from the site. Where provided for in the decommissioning plan, some items of contaminated equipment may be decontaminated at the site in order to bring them into compliance with the clearance criteria. Further information on the management of scrap is given in Section 11.2.

11.1.3. Final report

A final report compiled at the end of the decommissioning process provides a comprehensive record of the work carried out and the results obtained. In this way, the report provides verification that the decommissioning process was carried out according to plan and that the objectives of the process were met. The final report can also assist in the planning and execution of similar decommissioning processes in the future and is of particular value in documenting the lessons learned as a result of having to deviate from the original decommissioning plan because of unforeseen events. It is common practice for a minimum retention period to be specified for the final report, typically 15–50 years, since it may be needed in the event of any future litigation. The content of the final report is illustrated in the following example from the decommissioning of a phosphoric acid plant in the Netherlands [66]:

(a) Historical information, documentation and references;
(b) A summary of the decommissioning project;
(c) A history of the organization and management of the project, including allocation of responsibilities and supervision, with comments on any variations from the initial plan;
(d) The applicable licences;
(e) The results of the preliminary inventory;
(f) An overview and description of the environmental monitoring programme and procedures, with any results or findings;
(g) An overview of the contaminated installation components that were identified;
(h) An overview of the methods applied for treating these components;
(i) The plan of action for each method;
(j) An inventory of the end point disposal of contaminated components;
(k) An overview of the release of equipment used;

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(l) A list of the tools and aids that were applied and released;
(m) A calculation of the doses received by workers and the public, records of which are to be retained for 35 years;
(n) An overview of the quantities and temporary storage of the radioactive waste produced;
(o) The transfer of radioactive material to third parties for the purpose of further processing;
(p) Remediation activities and procedures for the release of the site, with any necessary ongoing monitoring procedures.

11.1.4. Management of residues

The management of residues removed during the decommissioning of a phosphoric acid plant in Rotterdam, Netherlands, is described in Ref. [66]. The residues were categorized as either radioactive waste or chemical waste, depending on the radioactivity concentrations. These two categories of waste were managed in the following way:

(i) Radioactive waste: Radium rich scale and contaminated carbon and rubber having a total mass of 6.7 t were removed. The total ^{226}Ra activity was 7 GBq, implying an average activity concentration of more than 1000 Bq/g. The material was packed into 118 drums of 100 L capacity and transferred to the Centrale Organisatie voor Radioactief Afval (COVRA) along with the HEPA filters[26] used during decontamination operations. In order to meet the COVRA specification that the liquid content be less than 1%, the waste was dried by infrared heating before packing.
(ii) Chemical waste: Water used for high pressure water jet cleaning and having a total mass of 44 t was collected in 16 tank cars. Particles of radioactive scale were removed from the water by an industrial waste company but, because of the chemical impurities that remained dissolved within it, the water was classified as chemical waste and disposed of accordingly. The residual ^{226}Ra activity concentration was less than 1 Bq/L. A total of 750 t of phosphogypsum scale with a ^{226}Ra activity concentration of less than 1 Bq/g was also collected and classified as chemical waste.

[26] HEPA: High efficiency particulate air. A HEPA filter is a type of air filter that satisfies certain standards of efficiency, such as those set by the United States Department of Energy.

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FIG. 59. Typical lay down area for scrap.

11.2. MANAGEMENT OF SCRAP

Various contaminated scrap items are removed from wet process plants during periods of maintenance carried out as part of routine plant operation and during the eventual plant decommissioning process. Decontamination of these items can greatly facilitate the management of this scrap and opens up repair or recycling options that might not otherwise be available. In many cases, however, decontamination is not technically or economically feasible and the scrap, therefore, has to be managed as radioactive material. Many contaminated items take the form of metal components such as structural steel, gratings, pipes, valves, filter pans and vessels, for which refurbishment, repair or recycling by melting are often worthwhile options. If the metal is recycled by melting, the need for decontamination of the scrap metal can usually be avoided.

Generally, each site has designated 'lay down' areas for collecting and segregating scrap items and measuring their surface contamination levels (see Fig. 59). Items are segregated according to the route by which they will be managed. There are four main options for managing scrap at wet process plants:

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FIG. 60. Scrap designated for recovery of the metal content by melting.

(i) Off-site repair by a service company;
(ii) Off-site recovery of the metal by melting (see Fig. 60);
(iii) Off-site disposal in an industrial or hazardous waste landfill facility (see Fig. 61);
(iv) On-site disposal by burial, for instance in the phosphogypsum stack (see Fig. 62).

Procedures for the radiological monitoring of scrap leaving the facililty tend to vary. Some facilities routinely monitor individual items of scrap before they are loaded for transport. Other facilities rely on portal monitors located at the exit from the site to survey loaded trucks before departure.

11.2.1. Decontamination of scrap

There are significant variations in the types of contaminant and their radionuclide concentrations. Although vigorous washing is sometimes sufficient for removing surface contamination, techniques based on water jetting, chemical treatment or mechanical abrasion are usually necessary for removing more persistent contamination, such as the scale deposited in wet process plants.

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FIG. 61. Scrap designated for off-site disposal at a landfill facility.

FIG. 62. Scrap designated for on-site disposal by burial.

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Components that come into contact with acid are often protected by a rubber lining, which becomes progressively contaminated during plant operation. Rubber belts from belt filter systems also become contaminated. In Florida, USA, the contaminated surface layer of a long rubber belt from the belt filter system, including the accompanying transportation reel, was successfully abraded away using high pressure water jetting with a suitable combination of nozzles, pressure and water volume [53]. High pressure water was also used to decontaminate the rubber linings of the attack tank and the acid storage tank in a phosphoric acid plant, using remotely controlled jetting equipment and a suction system to remove and conserve the contaminated water. The mist generated during the decontamination operation was removed via a filter system. The water–air mixture was discharged using a demister and a high performance filter, thus minimizing any migration of radioactivity to the environment. Decontamination of rubber components is not always the chosen option, however. In the decommissioning of a phosphoric acid plant in the Netherlands [66], contaminated rubber was removed together with radium rich scale during dismantling of the plant. In this instance, the rubber was not decontaminated but, instead, was sent with the scale to a radioactive waste storage facility (see Section 11.1.4).

11.2.2. Management of contaminated scrap

Measurements were made on a large variety of scrap items at seven wet process facilities in Florida, USA, over the course of a year [275]. The total ^{238}U and ^{226}Ra activities contained within the items sampled were 106 and 322 MBq, respectively, and the total mass was 66 t. The mean activity concentrations were, thus, 1.6 Bq/g for ^{238}U and 4.9 Bq/g for ^{226}Ra. An analysis showed that more than half of the uranium activity resided in scrap destined for off-site disposal at landfill facilities (see Fig. 63), while 78% of the radium activity resided in scrap destined for burial at the site, usually in a phosphogypsum stack (see Fig. 64). Only a third of the items destined for off-site recycling or disposal exhibited gamma dose rates above background levels. For the four scrap management options (off-site repair, off-site metal recovery by melting, off-site disposal at a landfill facility and on-site disposal by burial), the situation could be summarized as follows:

(i) Only a few items were destined for off-site repair. These were decontaminated before leaving the site and were, therefore, excluded from the radiological analysis.

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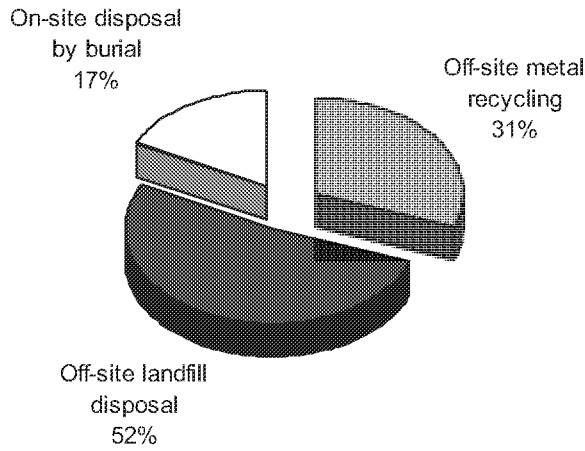

FIG. 63. Destination of ^{238}U activity in scrap arising from facilities in Florida, USA.

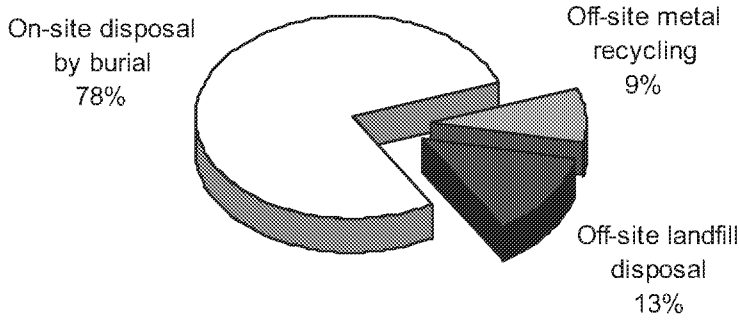

FIG. 64. Destination of ^{226}Ra activity in scrap arising from facilities in Florida, USA.

(ii) Most of the scrap metal (26 t) was sent to off-site metal recycling facilities. The mean activity concentrations of ^{238}U and ^{226}Ra were about 1.25 and 1.1 Bq/g, respectively.

(iii) The scrap sent for off-site disposal in landfill facilities (22 t) consisted predominantly of paper, cardboard and plastic. The mean activity concentrations of ^{238}U and ^{226}Ra were about 2.5 and 2 Bq/g, respectively.

(iv) The scrap retained for burial on-site consisted predominantly of process components such as filter cloths and fibreglass having little value for recycling. The mean activity concentrations of ^{238}U and ^{226}Ra were about 1 and 14 Bq/g, respectively.

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During the decommissioning of a phosphoric acid plant in Rotterdam, Netherlands [66], the following contaminated steel components were identified as suitable for recycling by melting:

(a) Parts of the tilting-pan filter;
(b) All steel pipes, including rubber linings;
(c) Vacuum seal tanks;
(d) Separators;
(e) Buffer tank.

The total activities of ^{226}Ra and ^{210}Pb contained within these items were 1.9 and 0.5 GBq, respectively, and the total mass was 62 t. The mean activity concentrations of ^{226}Ra and ^{210}Pb were, thus, about 30 and 8 Bq/g, respectively. The items were packed into seven closed IP-1 containers and transferred to a specialized melting facility. Objects that were too large, such as tanks, were cut into pieces before being packed.

11.3. OCCUPATIONAL EXPOSURE

The various decommissioning tasks are usually carried out according to standard operating procedures in order to ensure the effectiveness of the work and the safety of the workers involved. Health and safety precautions are incorporated into these procedures to ensure compliance with local OHS laws and regulations. Such precautions help to minimize the radiation exposure of workers. Similar considerations generally apply to the management of scrap.

Depending on the levels of exposure to radioactive material, decommissioning and scrap management work may have to be carried out in accordance with an appropriate radiation protection programme, as described in Ref. [4]. The requirements embodied in the radiation protection programme are likely to include the wearing of personal monitoring devices by selected workers to determine external exposure to gamma radiation and/or internal exposure from the inhalation of radionuclides in airborne dust. Both types of exposure can be significant because of the close proximity of workers to scale and other material with high radionuclide activity concentrations and because of the generation of airborne dust during welding, cutting, dismantling and decontamination activities. The potential for exposure is of particular concern when carrying out dismantling and decontamination work in confined areas such as tanks, especially when dry decontamination methods such as mechanical abrasion are used. During work of this nature, it is common for respiratory protection to be required as part of the standard OHS procedures and, in addition, exposure periods may

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have to be restricted. The use of high pressure water as an alternative to dry decontamination techniques, especially when, in confined areas, it is controlled remotely, as described in Ref. [53], is not only very effective in removing stubborn contamination but also considerably reduces the potential for exposure.

The decommissioning of a phosphoric acid plant at Rotterdam, Netherlands is described in Ref. [66]. The mean effective doses received by decommissioning workers over the duration of the decommissioning process are given in Table 37.

There is no published information on doses arising from the melting of scrap from wet process plants. However, a good estimate can be derived from the results of a detailed dose assessment conducted on an experimental melt of 38 t of uranium contaminated steel scrap from the South African gold mining industry [276]. The radioactivity levels in this scrap were similar to those reported in Ref. [275] for scrap from wet process facilities in Florida. The assessment of worker doses was based on the activity concentrations measured in the various process materials and in the air breathed by the workers. It was found that the inhalation of dust accounted for 96–100% of the dose. By making upward adjustments[27] to the South African results to account for differences in the activity concentrations of individual radionuclides in the uranium decay series, doses from the melting of metal scrap from wet process facilities were estimated and are given in Table 38. The mean annual committed effective dose for each category of worker is less than 1 mSv. The worker receiving the highest dose is the scrap processor. This worker operates the machinery for segmenting the scrap into sizes suitable for the furnace, a dusty operation involving exposure to airborne particles of contaminant during the full work period, assumed to be 2000 h/a. Should the contaminated scrap be mixed with uncontaminated scrap at the melting facility, some of the doses will, of course, be commensurately lower.

TABLE 37. DOSES RECEIVED BY WORKERS IN THE DECOMMISSIONING OF A PHOSPHORIC ACID PLANT [66]

Worker category	Mean effective dose (mSv)
Wet decontamination workers	1.2
Dry decontamination workers	<LLD[a]
Dismantling and construction workers and their assistants	<1.7
Supervisors	<LLD

[a] LLD: Lower limit of detection.

[27] These upward adjustments were 22% for contaminant particles, 69% for slag particles and 45% for flue gas particles.

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TABLE 38. DOSES EXPECTED TO BE RECEIVED BY WORKERS IN THE MELTING OF METAL SCRAP FROM WET PROCESS FACILITIES
(*derived from Refs [275, 276]*)

Worker	Mean annual committed effective dose (mSv)		
	Gamma radiation	Dust inhalation	Total
Scrap loader	0.0006	0.40	0.40
Truck driver	0.0002	Negligible	0.0002
Scrap processor	0.0001	0.99	0.99
Furnace operator	0.005	0.43	0.43
Casting worker	0.00003	0.30	0.30
Slag worker	0.02	0.52	0.55
Crane operator	0.0002	0.39	0.39

11.4. PUBLIC EXPOSURE

Since members of the public do not normally have access to sites on which decommissioning is being carried out, the potential for public exposure is very low. During the decommissioning of a phosphoric acid plant at Rotterdam, Netherlands [66], the annual effective dose received by the most highly exposed member of the public outside the facility was determined to be less than 0.4 μSv over the duration of the decommissioning process.

Doses received by members of the public as a result of the landfill disposal of scrap from wet process plants are likely to be insignificant. The mean radionuclide activity concentrations in the scrap are not expected to exceed 2–3 Bq/g and the possibility of any significant external and internal exposure is very small because the material is buried under controlled conditions designed to isolate the waste from the surrounding environment.

The doses received by members of the public as a result of exposure to steel recycled from wet process facilities have been estimated by considering the radioactivity content of uranium contaminated scrap originating from facilities in Florida, USA [275], together with the results of the dose assessment for steel recycled from similar scrap originating from mining activities in South Africa [276]. Allowances have been made for differences in radionuclide concentrations, principally the higher ^{226}Ra content in the scrap from Florida. In the original dose assessment carried out for mining scrap, the doses resulting from exposure of the public to gamma radiation from various steel products were calculated. It was found that the products giving rise to the highest doses were

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reinforcing bar for use in buildings and large foundry products such as components of large earthmoving equipment (the operators of which could be regarded as members of the public). The corresponding doses for steel recycled from wet process facilities are given in Table 39. The annual doses are all far below 1 mSv. In reality, it is unlikely that the steel used for product fabrication will originate entirely from contaminated scrap. Mixing with uncontaminated steel will take place either before or after the melting process. Consequently, the doses received by members of the public can be expected to be lower than those given in Table 39.

11.5. REGULATORY CONSIDERATIONS

The radionuclide concentrations in the materials encountered during the decommissioning of wet process plants and the management of scrap are frequently above 1 Bq/g and such activities clearly have to be considered for regulation as a practice. There is a potential for high occupational exposure to gamma radiation and radionuclides in airborne dust owing to the close proximity of workers to materials with elevated activity concentrations and the nature of the tasks involved in dismantling and decontamination operations. Moreover, residues designated as waste may need to be disposed of in a controlled manner in hazardous waste facilities. Nevertheless, annual doses received by decommissioning and scrap management workers appear to be below 1 mSv and doses received by members of the public are insignificant. It is important to bear in mind that standard procedures, particularly for decommissioning activities, generally incorporate health and safety precautions that are mandatory in terms of local OHS laws and regulations. While a formal radiation protection programme

TABLE 39. DOSES EXPECTED TO BE RECEIVED BY MEMBERS OF THE PUBLIC FROM EXPOSURE TO STEEL MADE FROM RECYCLED SCRAP DERIVED FROM WET PROCESS FACILITIES
(*derived from Refs [275, 276]*)

Material	Gamma dose rate (μSv/h)	Annual exposure period (h)	Annual effective dose (mSv)
Reinforcing bar used in walls	0.014	1500	0.02
Reinforcing bar used in floors and ceilings	0.025	1500	0.04
Large foundry products	0.057	2000	0.11

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may be desirable or necessary in some situations, it may not always be necessary to introduce additional regulatory controls specifically for purposes of radiation protection. The most appropariate regulatory option is likely to be a requirement for authorizaton in the form of a registration.

Residues arising from decommissioning and decontamination activities, while generally having elevated radionuclide activity concentrations of up to a few becquerels per gram, are, in most cases, likely to remain outside the scope of the Transport Regulations.

12. EXTRACTION OF URANIUM FROM PHOSPHORIC ACID

Phosphoric acid was once an important source of uranium [277], but subsequently, during the slump in uranium prices in the 1980s and 1990s, uranium extraction at phosphoric acid plants declined to the point where, from 1997 onwards, no further production is known to have taken place. Now, as a result of more favourable attitudes towards nuclear power and the depletion of uranium stockpiles, the price of uranium has recovered significantly and there is considerable interest once again in extracting uranium from phosphoric acid. Given that most of the uranium in phosphoric acid currently ends up in phosphate fertilizers, the extraction of uranium provides an added benefit, in that it reduces the potential for buildup of uranium in agricultural soils [278]. This section provides a summary of known best practices that may be adopted once uranium recovery from phosphoric acid is resumed in the near future.

Solvent extraction is currently regarded as the most highly proven and economic method of extracting uranium from phosphoric acid and will probably be the method of choice initially when production resumes. The ion exchange method is a promising alternative, but the technology is as yet unproven economically on a commercial scale. Continuing research into uranium recovery from phosphoric acid has resulted in a number of new, more powerful solvents as well as new ion exchange and membrane processes [279–281].

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12.1. THE SOLVENT EXTRACTION PROCESS

12.1.1. Process description

12.1.1.1. Main process

In general, all successful uranium recovery processes based on solvent extraction consist of five steps:

(i) Acid pretreatment;
(ii) Primary solvent extraction;
(iii) Raffinate post-treatment;
(iv) Secondary solvent extraction;
(v) Uranium refining.

There are also side stream operations such as residue treatment and strip acid preparation. The overall process is shown schematically in Fig. 65.

Acid pretreatment

Phosphoric acid is first cooled from 80°C to 30–50°C. This causes phosphogypsum impurities to come out of solution. These are usually removed by settling and returned to the phosphoric acid production process. Phosphogypsum also accumulates as scale in the heat exchangers and sometimes in the storage tanks. Activated carbon may be used to remove organic impurities from the phosphoric acid, after which the carbon is regenerated, typically with sodium hydroxide. The activated carbon absorbs radon which is not totally removed by the sodium hydroxide. Spent activated carbon is removed from the system as waste. If the uranium is to be extracted with a solvent that requires it to be in the U^{6+} state, the U^{4+} content of the phosphoric acid is oxidized to U^{6+} with air, oxygen, hydrogen peroxide, chlorine or nitric acid. If nitric acid is used, NO_x is emitted and usually has to be removed by a scrubber. If the uranium is to be extracted with a solvent that requires it to be in the U^{4+} state, the U^{6+} content of the phosphoric acid is reduced to U^{4+} by the addition of iron (scrap iron, iron balls or shredded iron) or ferrosilicon dust.

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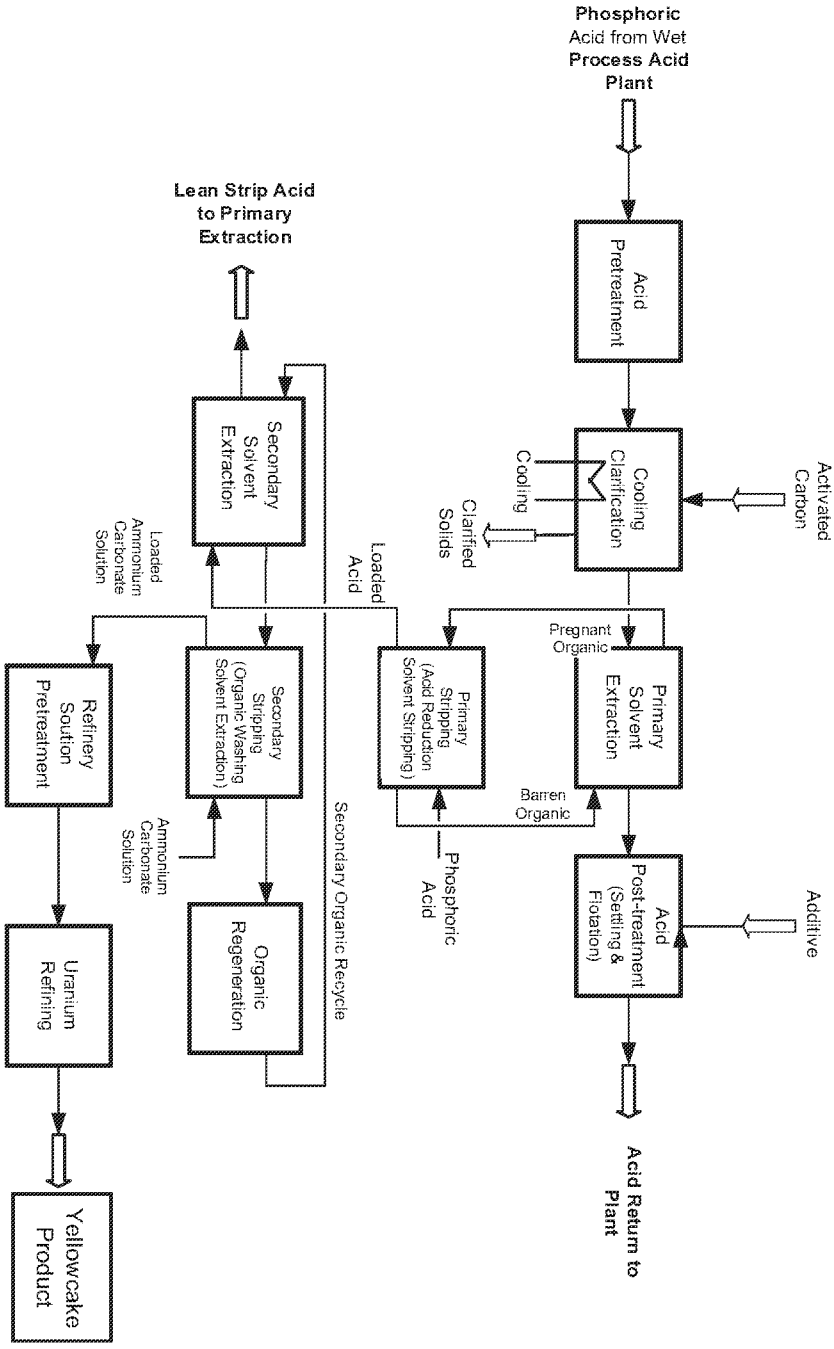

FIG. 65. Uranium recovery from phosphoric acid by solvent extraction.

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Primary solvent extraction

The solvent is a mixture of an extractant and a diluent (typically a petroleum compound). Prior to the suspension of uranium extraction operations in the late 1990s, the most commonly used extractant was a synergistic mixture of di-(2-ethylhexy) phosphoric acid (DEPA or D2EHPA) and tri-octylphosphine oxide (TOPO), which extracted uranium in the U^{6+} state. Octyl-phenylphosphoric acid (OPAP) and octyl-pyrophosphoric acid (OPPA), which extracted the uranium in the U^{4+} state, were also used. The pretreated phosphoric acid is contacted with the solvent in agitated mixer–settlers, in-line mixer–settlers or contacting columns. Typically, 3–6 stages of contact are used to remove 90–98% of the uranium from the acid. Depending on the solvent-to-acid ratio, the concentration of uranium attained in the solvent varies from 0.1 to 0.6 g/L, which is about 1–4 times the concentration in the original phosphoric acid. Stripping of the uranium from the solvent is accomplished by contacting the loaded solvent with phosphoric acid (27–50% P_2O_5). The strip acid is pretreated in one of two ways:

(i) If the uranium has been extracted in the U^{6+} state, iron is first added to the strip acid to convert its entire uranium content to the U^{4+} state. Since the addition of iron can cause rapid and significant iron phosphate scaling, all critical process lines are duplicated so that one can be washed out while the other is in operation. Sulphuric acid may also be added to minimize the precipitation of iron phosphate compounds.
(ii) If the uranium has been extracted in the U^{4+} state, an oxidizer is first added to the strip acid to convert its entire uranium content to the U^{6+} state. Traditionally, hydrogen peroxide has been used as an oxidizer, but oxygen, chlorine or nitric acid may also be used.

The concentration of uranium attained in the strip acid is typically 3–20 g/L.

Raffinate post-treatment

The phosphoric acid raffinate from the primary solvent extraction typically contains residual solvent at a concentration of about 100–500 ppm. Not only does this represent a loss of valuable solvent, but the diluent component can also cause damage to the rubber lined piping, evaporators and tanks that are downstream in the processing plant. The residual solvent is, therefore, removed in flotation cells. Using 5–10 such cells, the organic content of the raffinate can be reduced to less than 50 ppm.

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Secondary solvent extraction

The uranium in the strip acid from the primary solvent extraction is oxidized to the U^{6+} state using oxygen, hydrogen peroxide or nitric acid. The uranium is extracted using, as an extractant, a synergistic combination of DEPA and TOPO in several countercurrent stages employing 3–6 mixer–settlers. The uranium concentration attained in the solvent is about 15–30 g/L. The loaded solvent is washed with water to remove any entrained phosphoric acid. Using ammonium carbonate solution in two stripping stages, almost the entire uranium content is then stripped from the solvent. Since the stripped solvent has an affinity for ammonia, it is subjected to two stages of sulphuric acid washing to remove any ammonia before being recycled back to the front end of the process. Otherwise, the ammonia would react with the iron and phosphate in the oxidized feed acid and cause iron ammonium phosphate to be precipitated. The uranium concentration attained in the ammonium carbonate solution is generally about 15–30 g/L.

Uranium refining

The uranium in the ammonium carbonate solution is precipitated as ammonium diuranate ($(NH_4)_2U_2O_7$), ammonium uranyl tricarbonate ($(NH_4)_4UO_2(CO_3)_3$) or uranyl peroxide ($UO_4 \cdot nH_2O$). The precipitated uranium compound is known as 'yellowcake' because of its colour. The slurry is settled in a clarifier and extracted from the slurry feed either by centrifuging or filtration using pressure filters. The filtered cake is then sent to a dryer and optionally to a calciner. The calcined product contains more than 95% U_3O_8 together with small amounts of UO_2 and UO_3. It is usually drummed and sent by truck to a conversion plant where it is converted to UF_6 for enrichment. A typical truck shipment consists of about 18 t of yellowcake packaged in 40–50 drums, each containing 350–450 kg of product. Drums awaiting shipment are kept in a temporary storage area at the extraction plant accommodating up to 100–150 drums, thus providing sufficient capacity to cater for interruptions in trucking schedules. In areas of the plant where dry yellowcake is handled, the dust levels in the air are carefully controlled by ventilation, air scrubbers and HEPA filters.

12.1.1.2. Management of residues

The spent sodium hydroxide solution from the acid pretreatment step is sent to the acidic process water pond. The spent carbon may have a significant radioactivity content and its handling and disposal is, therefore, controlled

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appropriately. During the primary solvent extraction process, various residues are generated:

(a) An interfacial layer is formed, consisting of an emulsion of 1–5% solids in a similar volume of acid and solvent. The solids are insoluble in both acid and solvent. The layer is removed by suction pumping. While most of the acid and solvent can be removed from this residue using a pre-coat drum filter, chemical treatment or centrifuging, it is still one of the main causes of solvent loss. The formation of this residue is influenced by the effectiveness of the acid pretreatment step. The residue is disposed of either in the phosphogypsum stack or by burial on-site.

(b) Solid residues may be generated in the extraction mixer–settlers. If there is significant cooling of the acid, phosphogypsum and fluosilicates will precipitate. While some of these solids will end up in the interfacial layer, most will collect in the bottom of the settlers, which, therefore, have to be washed out periodically. About 20–40% of the content of the solids consists of acid. The solids, therefore, have a uranium concentration of up to 0.1 g/L. They are disposed of either in the phosphogypsum stack or by burial on-site.

(c) Solids are generated in the strip system when Fe^{2+} is oxidized to Fe^{3+} by the reduction of U^{6+}. This Fe^{3+} reacts with the phosphoric acid and any monovalent cations present to form iron phosphate compounded with ammonium, sodium or potassium. These solids generally end up at the bottom of the settler, but some may become entrained in the interfacial layer. The solids are removed periodically by washing out the solids with water or removing them manually. About 20–40% of the content of the solids consists of acid. The solids, therefore, have a uranium concentration of up to 8 g/L. They are disposed of either in the phosphogypsum stack or by burial on-site.

All the above disposal methods adopted in the past are unlikely to be practised in a future situation mainly owing to technological and regulatory improvements.

In the secondary solvent extraction, since the iron in the feed acid has been oxidized, there is significant precipitation of iron phosphate compounded with ammonium, sodium or potassium. These solids rapidly fill the settlers and must be removed as frequently as every few days. About 20–40% of the content of the solids consists of acid. The solids, therefore, have a uranium concentration of up to 8 g/L.

Throughout the extraction plant, there is a general tendency for uranium rich residues to accumulate on the surfaces of process equipment such as pipes, sumps and drains. Examples of such buildup are shown in Fig. 66.

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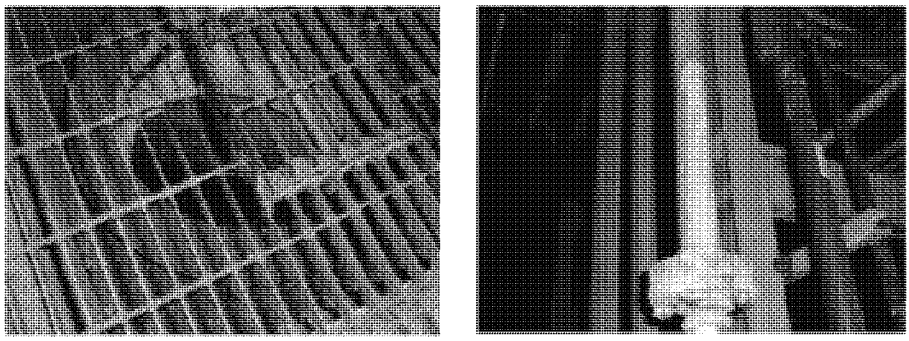

FIG. 66. Buildup of uranium rich residues within a solvent extraction plant.

12.1.2. Radionuclide activity concentrations

Pure uranium oxide (U_3O_8) contains ^{238}U and ^{234}U each at activity concentrations of 12 347 Bq/g and ^{235}U at an activity concentration of 568 Bq/g. It follows from the very purpose of the solvent extraction process, therefore, that many of the process materials and residues involved are likely to contain these uranium isotopes at very high activity concentrations. A summary of ^{238}U activity concentrations in the various process materials and residues associated with the solvent extraction process is given in Table 40 [282]. The dried yellowcake product has a ^{238}U activity concentration of the order of 10 000 Bq/g.

Radionuclides other than ^{238}U and ^{234}U, especially the remaining decay progeny of ^{238}U, are present in significant concentrations in materials associated with the acid pretreatment step. Here, residues consisting essentially of phosphogypsum and having a radionuclide composition similar to that of bulk phosphogypsum are precipitated as solid particles or deposited as scale. The spent activated carbon removed from the acid pretreatment step may have a significant radioactivity content resulting from the absorption of radon. From the point at which uranium is extracted from the phosphoric acid in the primary solvent extraction, the activity concentrations of radionuclides other than ^{238}U, ^{234}U and ^{235}U can be expected to be very low in relative terms. In absolute terms, however, such activity concentrations may still be significant. For instance, the activity concentration of ^{226}Ra in 65% grade yellowcake product is about 7.4 Bq/g.

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TABLE 40. URANIUM-238 ACTIVITY CONCENTRATIONS IN PROCESS MATERIALS AND RESIDUES ASSOCIATED WITH THE SOLVENT EXTRACTION PROCESS

Extraction process	Activity concentration (Bq/L)[a]
Primary solvent extraction:	
Loaded solvent	1300–7900
Loaded strip acid	40 000–260 000
Interfacial residue and, where used, filter pre-coat	Similar to or less than that in the incoming phosphoric acid[b]
Solids from extraction mixer–settlers	Up to 1300
Solids from strip system	Up to 100 000
Secondary solvent extraction:	
Loaded solvent	190 000–380 000
Loaded ammonium carbonate solution	190 000–380 000
Solids from mixer–settlers	Up to 100 000

[a] For solids, the activity concentration is given as becquerels per kilogram.
[b] For phosphoric acid produced from sedimentary rock in Florida, USA, the range of U-238 concentrations is 3500–5200 Bq/L.

12.1.3. Occupational exposure

12.1.3.1. Exposure pathways and exposure levels

Solvent extraction of uranium from phosphoric acid is not a labour intensive process. The number of workers employed per shift in an extraction plant is between 4 and 20, or even fewer in a plant with computerized process control systems. The potential for external gamma exposure is moderate because the workers tend to spend only short periods in areas of high dose rates and the concentrations of gamma emitting radionuclides such as radium and its progeny are relatively low. Furthermore, exposures to the yellowcake product are moderated by the shielding provided by centrifuge enclosures and the drums within which the product is packaged. Nevertheless, exposure to drums of yellowcake can become significant in the temporary storage area because of the number of drums stored. The dose rate on contact with a drum of yellowcake may reach 100 μSv/h, depending on the concentrations of ^{238}U decay progeny. The main potential exposure pathway is the inhalation of airborne dust, particularly for workers engaged in yellowcake drying and packaging activities. Ingestion of

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uranium as a result of contamination of skin and clothing is a concern, but more because of the chemical toxicity of uranium rather than its radiological effects.

12.1.3.2. Monitoring techniques for workers

External exposure is monitored using personal dosimeters (LiF TLDs or Al_2O_3:C OSLDs) worn on the chest and extremity dosimeters worn on the fingers. Monitoring of dust activity concentrations in the air, particularly in areas where yellowcake is handled, is carried out using stationary air sampling or personal air sampling. Workers who routinely handle yellowcake may be monitored using urine analysis, typically on a quarterly basis, to confirm that intakes of uranium continue to be low. The external surfaces of drums of yellowcake are checked with surface contamination monitors before shipping.

12.1.3.3. Effective dose

Although published data on annual effective doses received by workers in past operations are not available, reports suggest that such doses are usually not more than a few millisieverts and well below the occupational dose limit of 20 mSv.

12.1.3.4. Measures to reduce doses

Spillages can lead to workers being unexpectedly exposed to material with high activity concentrations. For instance, if the loaded solvent from secondary solvent extraction is spilled on the floor area surrounding the process equipment (typically a concrete pad), evaporation of the solvent can cause the uranium concentration to rise far above the normal level of 15–30 g/L. If all the solvent evaporates, the uranium content of the residue can be as high as 30%. At this level, the activity concentrations of ^{238}U and ^{234}U will each be almost 4×10^6 Bq/L. Such exposures can be avoided if care is taken to prevent such spillages and, if they do occur, to keep the area around the solvent extraction system flushed with water to prevent the buildup of high activity residues.

The use of thick, concrete walls for the construction of the yellowcake storage area has been found to provide effective shielding from the high dose rates in that area. In this way, the external exposure of workers on the other side of the wall is reduced to levels where no special precautions need be taken against external exposure.

Other measures that are known to be effective in reducing occupational exposure in solvent extraction plants include:

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(a) The adoption and enforcement of procedures to ensure that equipment, especially air filtration equipment, is properly maintained;
(b) The adoption and enforcement of good, general housekeeping measures, including the removal of settled dust and of sediments that build up on equipment such as structural steel, pipes and drains (see Fig. 66), so that the levels of contamination in the plant remain under adequate control;
(c) The use of smooth, hard finishes, such as epoxy coatings on floors and walls, to improve the effectiveness of routine cleaning and to facilitiate the cleanup of spillages;
(d) The provision of suitable bounded areas (berms and sumps) around process equipment having the greatest potential for major spillage;
(e) Maintenance of high levels of worker training and awareness;
(f) The provision of protective clothing, footwear barriers and decontamination facilities;
(g) The provision of respiratory protective equipment for certain tasks such as the changing of air filters, where engineering controls and administrative measures alone are not sufficient to control worker exposures adequately;
(h) Restrictions on eating, drinking and smoking in certain areas;
(i) Ensuring the effectiveness of administrative controls, such as the designation of controlled and supervised areas and the maintenance of strict access control.

12.1.4. Public exposure

There are normally no significant exposure pathways to members of the public from solvent extraction facilities. Liquid effluents are not discharged without adequate treatment. Gaseous discharges from ventilation systems are controlled by scrubbers and HEPA filters. Most of the radioactive residues generated by the process are recycled back to the process or, where disposed of as waste, are buried on the site, either in the phosphogypsum stack or nearby. The traditional practice of on-site burial in or next to the phosphogypsum stack may have to change in future to meet the changing regulatory requirements in respect of waste management practices. If future phosphogypsum stacks are no longer to be treated as disposal sites but, instead, as temporary holding areas pending future use of the phosphogypsum, then radioactive waste from the solvent extraction process will have to be kept separate and transported off the site to a suitable radioactive waste disposal facility.

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12.2. OTHER PROCESSES FOR THE EXTRACTION OF URANIUM

12.2.1. Ion exchange extraction

Ion exchange is a potentially attractive process for uranium recovery from phosphoric acid, presenting both challenges and opportunities [283, 284]. Compared with the solvent extraction process, the ion exchange process requires fewer pretreatment and post-treatment steps and offers potential economic advantages. The technology is, as yet, unproven on a commercial scale, but pilot testing, which is well advanced, has indicated several provisional but nonetheless positive conclusions. Compared with the solvent extraction process, the ion exchange process:

(a) Is potentially advantageous from an environmental point of view, because it avoids the generation of (radioactive) solvent extraction residue;
(b) Is better suited for feed phosphoric acid with uranium concentrations of less than 300 mg/L;
(c) Tends to have lower capital and operating costs for low uranium concentrations in the feed acid;
(d) May be tolerant of higher process temperatures (up to 80°C), a potentially significant cost saving as compared with solvent extraction, which may require the acid feed to be reheated on return to the phosphoric acid plant;
(e) May be more tolerant of organic acids in the feed acid;
(f) Eliminates the requirement for post-treatment of phosphoric acid raffinate;
(g) When used as a fluidized bed system, is tolerant of solids in the feed acid, implying a reduced need for clarification in pretreatment steps.

12.2.2. Solid membrane extraction

Uranium can be removed directly from phosphoric acid in a single step using porous membranes. This process yields very pure phosphoric acid and efficient uranium recovery in a single stage. However, the recovered uranium is a supersaturated concentrate containing chemical impurities that have also been removed from the acid. These impurities must be separated and removed as a waste stream. The membranes themselves are likely to become repeatedly clogged and quickly worn out, necessitating vigilant, well-trained operators and an effective, well-supervised maintenance and renewal regime. The disposal of the impurities removed from the process and of the spent membranes may have radiological implications.

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12.2.3. Liquid membrane extraction

Liquid membrane extraction is based on an emulsion containing both a liquid membrane extractant and a stripping solution. The extractant could be one of those used for solvent extraction, such as OPAP or DEPA–TOPO. Uranium is removed from the surfactant-stabilized membrane in an aqueous stripping phase. Very high uranium recoveries are achieved. A coalescent breaks down the uranium laden emulsion for recovery.

12.3. REGULATORY CONSIDERATIONS

Owing to the very high activity concentrations of uranium isotopes and other radionuclides in the yellowcake product and most of the intermediate process materials and residues, the extraction of uranium from phosphoric acid, regardless of the process used, is unquestionably regulated as a practice. Experience with extraction plants operated in the past has shown that workers received committed effective doses that under normal circumstances did not exceed a few millisieverts per year. There are no significant exposure pathways to members of the public. However, a formal (and effective) radiation protection programme, which includes a comprehensive monitoring programme, is the only way to ensure that workers do not receive much higher doses. Further details on the content of such a programme are given in Ref. [4]. In addition, the disposal of the radioactive waste generated by the solvent extraction process has to be carried out under controlled conditions. Consequently, the most appropriate regulatory option is a requirement for an authorization in the form of a registration or licence, the choice depending very much on the national approach. In many countries, the fact that uranium extraction is part of the front end of the nuclear fuel cycle necessitates that the authorization be in the form of a licence.

Owing to the high activity concentrations, the transport of yellowcake off the site and of any radioactive waste destined for off-site disposal falls firmly within the scope of the Transport Regulations.

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13. PRODUCTION OF ELEMENTAL PHOSPHORUS BY THERMAL PROCESSING OF PHOSPHATE ROCK

Thermal processing of phosphate rock to produce elemental phosphorus using the so-called electric furnace method was developed in the USA from 1933 onwards by the Tennessee Valley Authority (TVA) and was widely used to produce phosphoric acid during the period 1934–1977 in countries such as Canada, China, Germany, Kazakhstan, Netherlands and the USA [45].

In the past, phosphate rock was also thermally processed using the so-called blast furnace method. This process, which was originally used during the period 1929–1939 [45], had the advantage of being able to make use of low grade phosphate rock, provided that the main impurity was silica, with both iron oxide and alumina causing less difficulty in production than was the case for the wet process. In the late 1940s, the TVA investigated further improvements to the blast furnace process [285]. An attempt to revive the process in the late 1960s foundered on the high cost of coke [286], leaving the electric furnace method as the only method in use.

The thermal process has been used mainly for the production of high purity ('furnace grade') phosphoric acid, which is a constituent of products such as industrial chemicals, insecticides, detergents, food additives and feeds. Although the process still plays an important role in phosphoric acid production worldwide, its use has declined from past levels. At the end of 2001, one of the last two elemental phosphorus production facilities in the USA was shut down, leaving only one facility (at Soda Springs, Idaho) in operation in that country. Another facility continues to operate at Vlissingen, Netherlands. More recently, significant increases in the price of sulphur (a source of sulphuric acid used extensively in the wet process) have created conditions for a resurgence of interest in the thermal process. In China, for example, the nature of energy production, largely based on hydroelectric generation at a local level, has supplied inexpensive power to phosphoric acid plants for many decades. Since thermal acid production is very energy intensive, this advantage has been decisive in retaining a large thermal phosphorus production capacity in China, despite the fact that more recent joint ventures with Western companies have now brought wet acid production, as well as MAP and DAP production, to China on a large scale.

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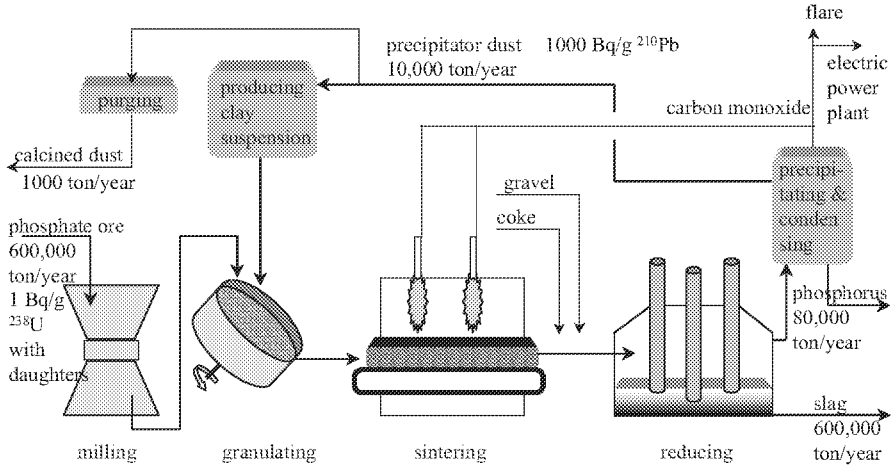

FIG. 67. Schematic representation of the thermal phosphorus process used by TIBV (from Ref. [287]). The numerical values are representative only and may vary considerably, depending on the characteristics of the phosphate rock feedstock.

13.1. PROCESS DESCRIPTION

13.1.1. Main process

Sintered pellets produced from finely powdered phosphate rock are fed into an electric arc furnace together with gravel and coke. The reduction of the phosphate produces elemental phosphorus along with calcium silicate slag, carbon monoxide and calcium fluoride according to the following chemical reaction:

$$2Ca_{10}F_2(PO_4)_6 + 30C + 12SiO_2 \rightarrow 3P_4 + 30CO + 6(3CaO{\cdot}2SiO_2) + 2CaF_2$$

A schematic representation of the process used at a plant operated by Thermphos International BV (TIBV) in the Netherlands (formerly part of Hoechst Holland NV) is shown in Fig. 67. This plant produces 80 000 t of elemental phosphorus, 600 000 t of calcium silicate slag and 4000 t of ferrophosphorus annually. The phosphate ore is first milled to a fine powder, which is then fed to a rotating granulator disc together with a binder consisting of a suspension of clay in water together with recycled precipitator dust. The rotation of the disc results in the formation of pellets. The pellets are fed to the front end of a slowly rotating sintering grate. They pass through a drying zone maintained at a temperature of up to 300°C and are then sintered to hard spheres

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under two large burners at a temperature of about 800°C. The pellets then pass through a cooling zone. The heat released from the pellets is directed to the drying zone. The pellets are then conveyed to an intermediate storage facility where they are stored in large silos in readiness for feeding to the electric furnaces. In sintering plants operating in other countries, the sintering process may differ in that the phosphate rock is not milled and a higher sintering temperature is used.

The sintered phosphate feedstock material is fed into an electric arc furnace together with the gravel and coke. The chemical reaction in which phosphate ore is reduced to elemental phosphorus takes place at temperatures exceeding 1500°C. The elemental phosphorus leaves the furnace as a gas, together with the carbon monoxide formed during the reaction. After removal of entrained dust, the gases are cooled, causing the phosphorus to condense to a stream of liquid phosphorus.

Production of phosphoric acid from elemental phosphorus is reasonably straightforward. Liquid elemental phosphorus is burned in air and the resulting P_2O_5 is then hydrated to create furnace grade phosphoric acid. The overall reaction may be characterized as:

$$P_4 + 5O_2 + 6H_2O \rightarrow 4H_3PO_4$$

13.1.2. Management of residues

The calcium silicate slag produced during the process flows continuously from the furnace. Trace amounts of iron are also reduced in the furnace. These form a separate slag, ferrophosphorus, containing approximately 75% iron, 25% phosphorus and small amounts of other metals. The calcium silicate slag is a stone-like by-product with applications as a construction material for roads, dykes and possibly dwellings. It is a good substitute for gravel, the mining of which can have undesirable environmental consequences through the formation of gravel pits. When used in a road bed, especially when used together with steel slag, its angular structure imparts greater resistance to subsidence.

At the high temperatures prevailing in the furnace, volatile inorganic substances, metals and radionuclides evaporate and condense on dust particles. The dust is trapped in electrostatic precipitators. In the TIBV plant, about 10 000 t of precipitator dust is produced annually, most of which is recycled back to the sintering plant. It is fed to slurry tanks where it is mixed with water and pumped to the 'slurry station' for reuse as a component of the binding suspension used for pelletizing the phosphate powder. When the volatile inorganic substances, metals and radionuclides contained within the precipitator dust reach the furnace for the second time, they evaporate again. In this way, these substances become enriched

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in the so-called precipitator dust cycle. High concentrations of volatile inorganic matter and metals cause instability in the operation of the furnaces. To control the concentration, 500–1000 t of precipitator dust are purged from the system annually by diverting the dust stream to a purge unit housed in the slurry station. The purge unit consists of a high pressure filter and a rotating calcining kiln where the pressed, lumped precipitator dust is calcined at temperatures of 400–500°C before being removed as waste. The recycling of precipitator dust in this manner reduces the amount of solid waste requiring disposal, but increases the emissions of radionuclides to the atmosphere. Modifications to the precipitator dust recycling process have since been made to reduce these radionuclide emissions [288]. In plants in other countries, it has been more common in the past for the precipitator dust to be disposed of rather than recycled back to the process.

Calcined precipitator dust produced in past operations at the TIBV plant at a rate of 500–1000 t/a is stored on-site. Calcined dust from current operations is being stored at the centralized COVRA radioactive waste storage facility. Storage allows the ^{210}Pb to decay sufficiently for the material to be disposed of in a landfill facility after immobilization in cement [289]. For instance, after 150 years, the ^{210}Pb activity concentration will have fallen from 1000 Bq/g to 10 Bq/g. The material at COVRA is stored in containers fitted with plastic linings and stacked in a purpose-built storage building. To avoid taking up excessive space in the storage building, immobilization in cement will be carried out only after the decay storage period has elapsed.

13.2. RADIONUCLIDE ACTIVITY CONCENTRATIONS

During the sintering process, ^{210}Po, which has a half-life of 138 d, volatilizes and escapes from the feedstock material. It passes through the scrubbers that wash the sinter gases and is emitted to the atmosphere. Most of the ^{210}Pb, which is less volatile than ^{210}Po, remains in the sintered feedstock.

In the furnace, the radionuclides above ^{222}Rn in the ^{238}U decay chain (see Appendix I) remain in the melt and become part of the calcium silicate slag. Of the radionuclides escaping from the melt, the two most important in terms of gamma dose (^{214}Pb and ^{214}Bi) grow back into the slag after about two weeks. Since approximately one tonne of slag is formed per tonne of phosphate rock feedstock, the activity concentrations of ^{238}U, ^{214}Pb and ^{214}Bi in the slag are similar to those in the feedstock (about 1 Bq/g). The ^{222}Rn escaping from the melt leaves the furnace along with the carbon monoxide. Only those radionuclides below ^{222}Rn in the ^{238}U decay chain end up in the precipitator dust. Consequently, the ^{238}U activity concentration in the precipitator dust is low, with a maximum

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value of about 1 Bq/g. The behaviour of the radionuclides in the precipitator dust can be summarized as follows:

(a) The short lived progeny of radon (^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) decay within a few hours.
(b) In the TIBV process, the relatively long lived ^{210}Pb (half-life of 22 a) builds up in the precipitator dust during the recycling process to an activity concentration of about 1000 Bq/g, representing a thousandfold enrichment of this radionuclide. Owing to the loss of ^{210}Po during the sintering of the pellets, the activity concentration of ^{210}Po in the precipitator dust is initially only about 60 Bq/g, considerably lower than the activity concentration of ^{210}Pb. The half-lives of ^{210}Bi and ^{210}Po (progeny of ^{210}Pb) are 5 and 138 d, respectively, and after about four half-life periods, these progeny are again present in the precipitator dust at nearly the same activity concentration as that of the parent radionuclide, ^{210}Pb.

Very little radioactivity migrates to the elemental phosphorus product or to the ferrophosphorus slag. The phosphorus contains ^{226}Ra at an activity concentration of 0.03 Bq/g, while the ferrophosphorus contains ^{238}U series radionuclides each at an activity concentration of 0.03 Bq/g.

13.3. OCCUPATIONAL EXPOSURE

13.3.1. Exposure pathways

Phosphorus plant workers are exposed to airborne dust originating from the phosphate rock, but since the activity concentrations are low, the exposure levels are not significant. In the case of the TIBV plant, where the recycling of precipitator dust is carried out, the activity concentrations of ^{210}Pb and ^{210}Po in the dust are approximately 1000 times higher than in the phosphate rock. This then becomes the main source of exposure of plant workers.

13.3.2. Exposure of plant workers

13.3.2.1. Monitoring techniques

This section describes the monitoring techniques used for workers at the TIBV plant. To determine the intakes of radionuclides by workers, TIBV makes measurements using personal air sampling equipment comprising a battery powered air pump connected by a flexible tube to a filter located in a filter holder [287].

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During the period 1998–2003, TIBV sampled the inhalable dust fraction using an IOM sampling cassette (see Fig. 3). Since 2004, a thoracic sampler has been used instead (see Fig. 4) [290], in order to minimize dose assessment errors (see Section 3.3.2). The equipment is carried by the worker in such a way that a continuous sample of the air surrounding the worker passes through the filter. The dust is separated from the air and collected on the filter. The worker carries the personal air sampler for the working shift of 8 h.

Alpha and beta activities on the filter are measured using a proportional counter capable of discriminating between alpha and beta radiations. The achievement of the necessary statistical accuracy requires a counting time of 5 d, necessitating the use of a 10 channel counter. The activity of ^{210}Pb on the filter cannot be measured directly because the beta emission from this radionuclide is very weak. It is determined, instead, from the beta emission from ^{210}Bi, which has a maximum energy of 1.16 MeV. To ensure that ^{210}Bi reaches radioactive equilibrium with its parent ^{210}Pb, it is necessary to retain the filter for three weeks before carrying out the measurement. The alpha emission from ^{210}Po has an energy of 5.3 MeV, allowing the activity of this radionuclide to be measured directly.

The worker's radionuclide intake is determined from the count rates obtained from the filter, the rate of air flow through the filter, the worker's breathing rate (usually taken as 1.2 m^3/h) and the exposure time (typically 8 h). For those work functions associated with the highest intakes and a wide confidence interval, the frequency of measurement is increased in order to narrow the confidence interval and thus obtain a more accurate dose assessment.

Dissolution tests conducted at TIBV indicate that the slowest lung absorption type (S) is the most appropriate for dose calculation purposes. Assuming this lung absorption type, the committed effective doses per unit intake of radionuclide activity have been determined for ^{210}Pb and ^{210}Po as functions of AMAD and GSD. The results are shown in Figs 68 and 69. Since, for AMADs of 0.5–5 μm, the dose coefficients remain within a relatively small range, TIBV uses dose coefficients representative of this range, namely 5.8 and 4.2 μSv/Bq for ^{210}Pb and ^{210}Po, respectively.

TIBV has carried out a dust characterization using a cascade impactor to determine the activity distribution as a function of particle size. The results indicate that there is considerable activity associated with particles having an AMAD greater than 0.5–5 μm, especially where workers produce the dust themselves during cleaning work. Under such circumstances, a considerable part of the activity intake is believed to originate from dust particles with AMADs of 5–10 μm and greater. The implication for a worker involved in cleaning work with freshly produced airborne dust is that the dose determined on the basis of an AMAD of 0.5–5 μm will be overestimated because of the lower dose coefficients associated with these larger particles.

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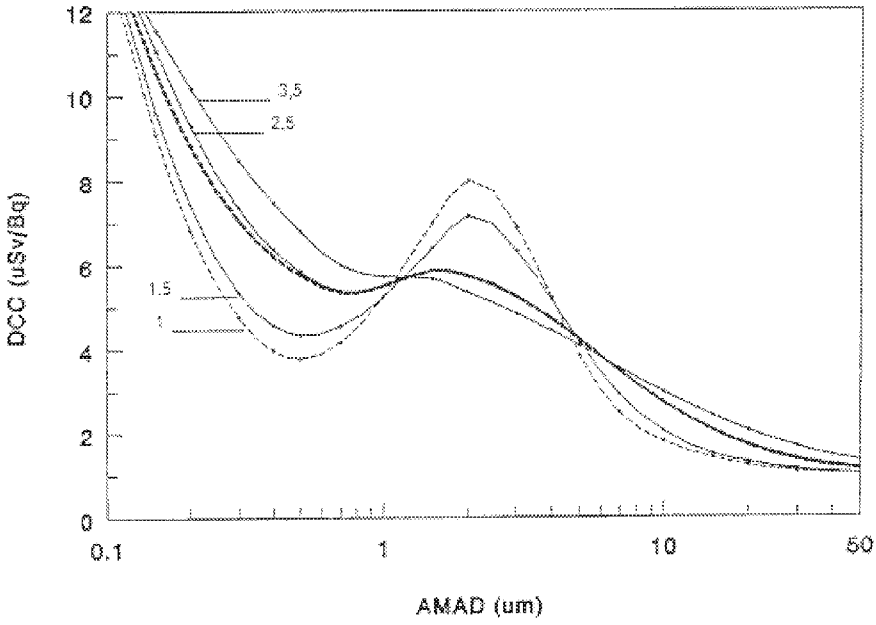

FIG. 68. Dose per unit intake for ^{210}Pb, lung absorption type S, as a function of AMAD and GSD.

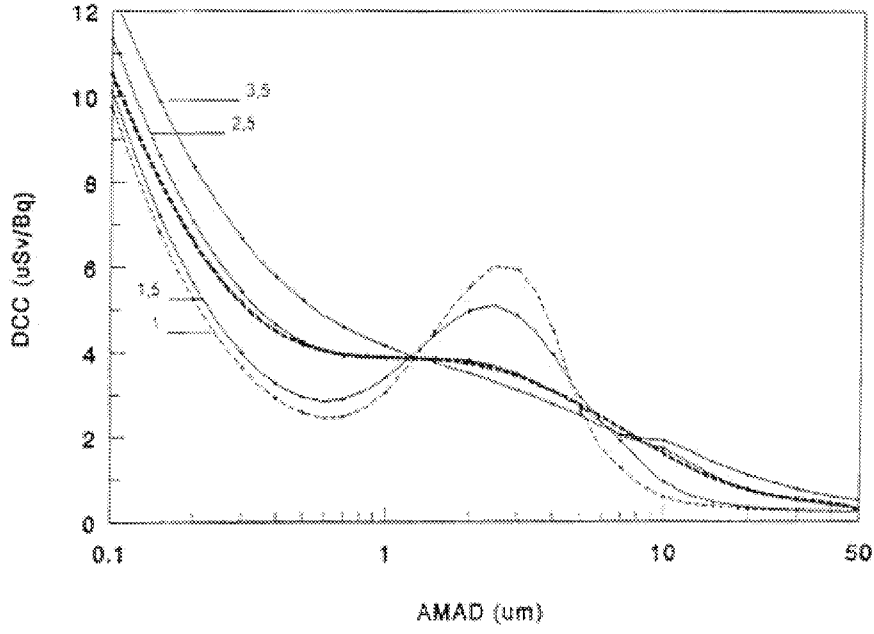

FIG. 69. Dose per unit intake for ^{210}Po, lung absorption type S, as a function of AMAD and GSD.

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13.3.2.2. Effective dose

To simplify the dose calculation, it can be assumed that all the inhaled alpha activity originates from ^{210}Po and all the inhaled beta activity originates from ^{210}Pb. The results of the dose assessments carried out since 2004 at the TIBV plant using thoracic sampling devices [288] are given in Table 41. The average

TABLE 41. DOSES RECEIVED BY WORKERS AT THE TIBV THERMAL PHOSPHORUS PLANT [288]

Worker	Annual committed effective dose (mSv)			Contribution of Pb-210 to dose (%)[a]	Average dose for 1998–2003 assessed using 'inhalable dust' samplers (mSv) (for comparison)
	Average	Standard deviation	90% confidence interval		
Sintering plant:					
Indoor operator	0.67	0.57	0.48–0.86	64	1.63
Granulating operator	0.47	0.31	0.31–0.63	52	1.03
Slurry operator	0.48	0.42	0.28–0.68	60	0.66
Cleaning operator	0.74	0.45	0.61–0.87	53	2.17
Overall	0.57	0.39	0.51–0.63	54	1.31
Phosphorus plant:					
Filtration	0.23	0.07	0.18–0.28	63	0.39
Condensation	0.28	0.12	0.21–0.35	58	0.52
Electrode welder	0.33	0.16	0.25–0.41	66	0.63
Daytime operator	0.29	0.12	0.19–0.39	72	0.95
Furnace feed	0.44	0.42	0.29–0.59	67	0.72
Slag operator	0.34	0.21	0.17–0.51	59	0.56
Slurry operator	0.41	0.23	0.32–0.50	70	0.64
Cleaning operator	0.48	0.27	0.36–0.60	72	1.59
Overall	0.33	0.19	0.30–0.36	70	0.90
Supervisors	0.26	0.17	0.22–0.30	65[b], 73[c]	0.65[b], 1.37[c]
Overall (both plants)	0.43	0.35	0.38–0.48	61	1.09

[a] Obtained from 1998–2003 measurements.
[b] Shift supervisor.
[c] Assistant supervisor.

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annual effective doses are well below 1 mSv throughout the plant, with an overall average of 0.43 mSv. The highest dose (upper 90% confidence limit) is 0.87 mSv, received by the cleaning operator in the sintering plant. The contribution of ^{210}Pb to the total dose is about 50–70%, with ^{210}Po accounting for the rest. Also shown in Table 41 are the average doses assessed during 1998–2003 by sampling the inhalable fraction using IOM cassettes. A comparison of the two sets of results gives an indication of the amount by which the dose was overestimated in the past as a result of using an AMAD range of 0.5–5 μm, when a substantial fraction of the activity was associated with particles with AMADs greater than 5 μm (see Section 13.3.2.1). Overall, the doses were overestimated by a factor of 2.5.

The variation in assessed doses is large because work activities can differ from day to day and the concentrations of radionuclides in the air fluctuate widely. In earlier monitoring programmes at TIBV, it was found that the dose assessed over the standard one day measuring period varied from zero up to five times the average daily value [287]. The achievement of small confidence intervals for every work function would require a prohibitively large number of measurements being taken. For all the functions together within one plant, however, the confidence interval was considered acceptable.

The dose variations depend on the process (which is predetermined) and on the specific working conditions and work practices that affect the exposure of the worker (which are less easy to predict). The following examples were found at the TIBV plant:

(a) Two workers carried out the same cleaning work on the same floor. After the work was completed, the first worker was covered in dust while the other was clean. The first worker used a broom for certain cleaning activities whereas the other used only the prescribed vacuum cleaner. Both operators inhaled the same 'background' air. The committed effective dose assessed for the first worker was 0.02 mSv over just that one working shift, while the dose for the second worker was almost zero. This demonstrated that the background air was essentially free of radionuclides and that the dose received was influenced almost entirely by the working activities and especially the way in which they were carried out.

(b) Some workers, such as electrode welders, work in an environment in which there is no contamination of surrounding surfaces and, thus, no possibility of receiving a dose from the resuspension of dust. It was demonstrated, however, that the air in such a workplace was contaminated by the activities necessary to remove slag (into slag beds situated immediately next to the furnace building) and ferrophosphorus from the furnace.

(c) Large surface areas of some workplaces were contaminated by dry precipitator dust containing ^{210}Pb and its progeny at an activity

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concentration of 1000 Bq/g. This contamination did not always lead to a dose; daily monitoring of workers in these areas often gave an assessed dose of zero. Simply walking through the contaminated area did not necessarily lead to inhalation of the dust because of the distance between the resuspension point (the feet) and the inhalation point (the nose and mouth). However, if work had been carried out at a fixed location in that area, the resuspended particles could have been inhaled and would have led to an effective dose of 0.04 mSv committed over the course of just one working shift. On one occasion, a compressed air hose broke loose from its connection and dust was blown from the floor over a period of several minutes. The exposure measured over the full working shift corresponded to a dose of 0.12 mSv committed in just that one shift.

(d) Measurements showed that it was possible to create concentrations of dust that, if inhaled, would result in an effective dose of up to 1 mSv being committed in a 1 h period if highly contaminated parts of an installation were subjected to various mechanical procedures to remove surface contamination, thereby causing the resuspension of contaminant particles into the air. Contamination levels of several hundred becquerels per square centimetre have been measured on internal surfaces of process equipment. Under normal circumstances, workers are not exposed to these high levels of contamination but, when the installation is opened for maintenance or repair, measures have to be taken to prevent large inhalation doses from being received.

13.3.2.3. Measures to reduce doses

At the TIBV plant, by taking more measurements at the same time at different places in a working area and comparing them with earlier measurements, taking the working and process conditions into account, it has been possible to determine the pathways by which the radionuclides liberated from the process reached the workers involved. This has allowed dose reduction measures to be identified. An aerosol monitor giving 3 h average measurements has been used to study the fluctuations in concentration of alpha and beta emitting radionuclides in air. With this device, it is possible to identify sources of dust responsible for enhancing air concentrations.

Measures taken at the TIBV plant to reduce doses from inhalation of dust include the following:

(a) Conduct of large scale continuous cleaning operations;
(b) Renewal and coating of floor surfaces to enable them to be decontaminated more easily;

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FIG. 70. Half-mask respirator.

(c) Prevention of contamination by the installation of new measuring instruments and automation to monitor and control the process;
(d) Improved ventilation at the ferrophosphorus outlet of the furnaces;
(e) Relocation of the slag beds away from the furnace building;
(f) Installation of central vacuum cleaning systems to avoid the need to open and empty mobile vacuum cleaners.

In addition, safety procedures attempt to minimize the possibility of higher exposures. If a vessel, sintering oven or furnace has to be opened and workers have to enter, the surface contamination levels are measured first. If the contamination level is less than 0.25 Bq/cm^2, workers may enter without protective equipment. If the contamination level is 0.25–10 Bq/cm^2, a half-mask respirator with an assigned protection factor of 20 is worn (see Fig. 70). If the contamination level exceeds 10 Bq/cm^2, a full face mask respirator with remote air supply is worn (see Fig. 71). These criteria have been derived conservatively from the results of measurement programmes, but are intended to apply only to inspection work or to other activities that do not produce significant amounts of dust. For activities producing dust, a full face mask respirator with remote air supply is worn, irrespective of the surface contamination level.

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FIG. 71. Full face mask respirator with remote air supply.

13.4. PUBLIC EXPOSURE

13.4.1. Discharges from the plant

13.4.1.1. Inhalation exposure

During thermal phosphorus production, the radionuclides above ^{222}Rn in the ^{238}U decay series remain in the slag and are, therefore, not emitted to the atmosphere. Radon escapes from the melt and its short lived progeny ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po decay within a few hours. Exposures of members of the public to radon and its short lived progeny, as well as to ^{210}Bi, are negligible [291]. The only radionuclides of interest from a public exposure point of view are ^{210}Po and ^{210}Pb. The relatively volatile ^{210}Po escapes from the pellets during sintering and most of it is emitted to the atmosphere, despite intensive scrubbing of the exhaust gases. Although ^{210}Pb is less volatile, at the TIBV plant, the recycling of the ^{210}Pb rich precipitator dust can result in an annual emission of this radionuclide relative to ^{210}Po of up to about 50%, depending on the type of ore used in the process.

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Table 42 shows details for the two year period 1994–1995, when the majority of the ore was obtained from Florida, USA [292, 293], and for the two year period 2002–2003, when the majority of the ore was obtained from Mediterranean and Middle Eastern countries [294, 295]. During the former period, the emission of ^{210}Pb was only 8% of that of ^{210}Po. During the latter period, the total activity input (and hence the emission of ^{210}Po) was significantly lower, but the emission of ^{210}Pb rose to 41% of that of ^{210}Po.

Measurements have shown that the AMADs of the dust particles to which the radionuclides are attached are typically 0.5–1 μm and that the most appropriate lung absorption class is S. The committed effective dose per unit inhaled intake was determined from leaching tests to be 4.3 μSv/Bq for ^{210}Pb and 3.6 μSv/Bq for ^{210}Po [296]. A dose assessment conducted in 1998 showed that the inhalation dose received by a member of the public located in a village 4 km distant was 0.020 mSv/a [289]. Without the recycling of precipitator dust to the sintering plant, it was calculated that this dose would have been 2–5 times lower.

13.4.1.2. Ingestion exposure

Doses received by members of the public living near the TIBV plant were assessed by examining the following exposure pathways [289]:

(a) Ingestion of radioactive fallout from discharges into the atmosphere:
  (i) Soil→crops→humans;
  (ii) Soil→grass→cattle→milk→humans;
  (iii) Soil→grass→cattle→meat→humans;
  (iv) Water→shellfish/crustaceans→humans;
  (v) Water→fish→humans.
(b) Ingestion of radioactivity discharged into the surface water environment:
  (i) Water→shellfish/crustaceans→humans;
  (ii) Water→fish→humans.

TABLE 42. EMISSIONS of ^{210}Pb AND ^{210}Po FROM THE TIBV THERMAL PHOSPHORUS PLANT [292–295]

Period	Ore input (million t)	Proportion of Florida ore (%)	^{210}Po activity (GBq)		^{210}Pb activity (GBq)	
			Input	Emission	Input	Emission
1994–1995	1.186	58	1250.7	1008.9	1250.7	80.1
2002–2003	1.147	0.0	723.5	775.5	723.5	315.0

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TABLE 43. RADIONUCLIDE CONCENTRATION FACTORS USED FOR ASSESSING INGESTION DOSES

Radionuclide	Concentration factor		
	Mussels	Shrimps	Fish
^{210}Po	1000	50 000	2000
^{210}Pb	1000	1000	200

The concentration factors used for determining the activity concentration of radionuclides in marine organisms are given in Table 43. Radionuclide decay and ingrowth were taken into account in the dose assessment. The ingestion dose coefficients for ^{210}Pb and ^{210}Po were 0.69 and 1.2 μSv/Bq, respectively, as specified in the BSS [2]. The results of the assessment showed that the dose arising from ingestion of radionuclides discharged from the TIBV plant was very small — about 0.001 mSv/a.

13.4.2. Use of calcium silicate slag

13.4.2.1. Road construction

The use of calcium silicate slag as a construction material is subject to the requirements for existing exposure situations (see Section 3.1.1 and Ref. [2]). In terms of these requirements, workers are regarded as members of the public for the purposes of radiation protection. The exposure of workers involved in the construction of roads using calcium silicate slag is reported in Ref. [296]. Construction workers are exposed to gamma radiation from the material. The radionuclides ^{214}Pb and ^{214}Bi together contribute 99% of the total gamma dose. The external gamma dose rate 1 m above the mid-point of a layer of phosphorus slag 20 m square and 0.4 m thick was estimated, assuming the ^{238}U and ^{232}Th series radionuclides in the phosphorus slag to be in equilibrium with their respective parents. For ^{238}U series radionuclides, the dose rate was found to be 0.28 μSv/h per unit activity concentration (in becquerels per gram). The corresponding dose rates for ^{232}Th series radionuclides and ^{40}K were 0.43 and 0.03 μSv/h, respectively. These could be taken as maximum values, as increasing the dimensions of the slag layer had no effect on the dose rates. In practice, the average dose rate applicable to road construction workers is significantly lower, for the following reasons:

(a) The shielding effect of machines used in road construction reduces the dose rate to the operator by 50%.

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(b) The width of most roads is less than 20 m.
(c) The worker is not always in the centre of the road bed; the dose rate at the edge is approximately 50% lower.

On the basis of these practical considerations and measurements taken at a road construction site in the Netherlands, and assuming an annual exposure time of 1600 h, the effective dose received in a year by a road construction worker from gamma radiation originating from the slag was estimated to be 0.25 mSv per unit activity concentration of ^{238}U in the slag. The corresponding doses for ^{232}Th and ^{40}K were, respectively, 0.388 and 0.025 mSv per unit activity concentration. Assuming realistic dust levels, sustained for the same annual exposure period of 1600 h, the annual committed effective dose from the inhalation of airborne slag particles was estimated to be 0.03 mSv per unit activity concentration of ^{238}U or ^{232}Th (the same value applied to each radionuclide). The inhalation dose from ^{40}K was negligible. Assuming an ^{238}U activity concentration of 2 Bq/g (which is at the upper end of the normal range in phosphorus slag) and ^{232}Th and ^{40}K activity concentrations each of 0.05 Bq/g, the annual effective dose was thus 0.52 mSv from external gamma exposure and 0.06 mSv from dust inhalation, giving a total annual effective dose of 0.58 mSv.

During road construction, a nearby resident may be exposed to dust, but only for a few hours per day and for a construction period in that person's neighbourhood of a few days to a few weeks in the year of construction. Consequently, comparing the situation with that for a road construction worker, the maximum dose received by a member of the public as a result of the inhalation of phosphorus slag particles during road construction will be no more than a few microsieverts only in that year or those years in which construction work is carried out in that person's neighbourhood.

Once the road is constructed, a member of the public may be exposed to external gamma radiation through the use of that road. Doses received as a result of the incorporation of phosphorus slag from the TIBV plant into roads in the Netherlands have been estimated [296]. It was assumed that the exposure occurs in the middle of the road and that the phosphorus slag layer has a thickness of 0.4 m and a ^{238}U activity concentration of 1.25 Bq/g. The top layer of the road surface, which never contains phosphorus slag, was assumed to have a density of 2350 kg/m^3 and a thickness ranging from 0.06 to 0.19 m, depending on the type of road. The maximum exposure time is limited by the fact that the slag production level of the TIBV plant (600 000 t/a) accounts for less than 4% of the total road bed construction material required in the Netherlands. Therefore, the average exposure time was assumed to be 1.5 h per day. On the basis of these assumptions, the annual dose received by a member of the public was estimated to be about 0.060 mSv for a top layer thickness of 0.06 m, about 0.020 mSv for a

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top layer thickness of 0.13 m, and about 0.001 mSv for a top layer thickness of 0.19 m. These dose estimates are likely to be valid for both private and commercial road users. Commercial road users may spend more time on the road, but such time is usually spent on major highways, which have more than one top layer to obtain the necessary construction strength.

13.4.2.2. Dyke construction

A study commissioned by the Dutch Ministry of the Environment investigated the leaching behaviour of the radionuclides in phosphorus slag with a view to determining the radiological impact of using such material in the construction of dykes [289]. In a hypothetical situation in which all the dykes of the Ijsselmeer (the largest lake in the Netherlands) were assumed to have been constructed using phosphorus slag as a filler material, the maximum annual dose received by a member of the public was calculated to be 0.000 012 mSv; an insignificant level.

13.4.2.3. House construction

In principle, phosphorus slag can be considered for use in house construction and in this regard should be treated no differently from other potential construction materials containing elevated levels of natural radionuclides. However, any such application requires careful assessment on a case-by-case basis. The annual dose received by a house occupant depends on the activity concentration of the material and the nature and extent of its incorporation into the structure of the house. Two contrasting situations are highlighted in Ref. [289]. The use of phosphorus slag in very large quantities could be an unacceptable option because of doses being considerably higher than those associated with normal construction materials. As an extreme example, residing for a year on a surface formed entirely by a thick layer of phosphorus slag is estimated to give rise to an annual dose of 5 mSv. On the other hand, the incorporation of phosphorus slag into concrete used for foundation piles could be an acceptable option.

13.5. REGULATORY CONSIDERATIONS

The radionuclide activity concentrations in the phosphate rock feedstock and the calcium silicate slag may, in some cases, exceed 1 Bq/g by a moderate amount. In facilities that recycle the furnace dust extracted from the precipitator, the activity concentrations of ^{210}Pb and ^{210}Po may increase to several hundred

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becquerels per gram as they progressively accumulate in this dust. Consequently, in terms of the Standards, the production of phosphorus by the thermal process should be considered for regulatory control as a practice. The annual doses received by plant workers are less than 1 mSv, although there is clearly potential for doses several times higher if airborne dust in the furnace area is not adequately controlled. The decay storage of precipitator dust prior to its eventual disposal needs to be carried out under controlled conditions because of the high activity concentrations involved. The annual doses received by members of the public from discharges from the plant have been determined to be far below 1 mSv. The most appropriate regulatory option is likely to be a requirement for authorization, most probably in the form of a registration.

When using the calcium silicate by-product for the construction of structures such as roads and dykes, the doses received annually by construction workers and members of the public are far below 1 mSv and no restrictions on such use would appear to be necessary. The use of the material in the construction of dwellings, while not having been studied specifically, would appear to have the potential for giving rise to doses exceeding 1 mSv because of the likelihood of shorter exposure distances and longer exposure periods. Therefore, a situation specific dose assessment would be needed to determine the need for any restrictions on such use.

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Appendix I

URANIUM AND THORIUM DECAY SERIES

The ^{238}U and ^{232}Th series are the main decay series of interest. The ^{235}U decay series is less important for radiation protection purposes, except for the radionuclide ^{227}Ac, which can contribute significantly to inhalation exposure. If necessary, the presence of ^{235}U (and, by implication, its decay progeny) can be taken into account on the basis of the abundances of ^{235}U and ^{238}U in natural uranium (0.711 and 99.284%, respectively) — the corresponding ^{235}U:^{238}U activity ratio is 0.046. Details of the ^{238}U and ^{232}Th decay series, as reported in Ref. [297], are given in Tables 44 and 45, respectively.

TABLE 44. URANIUM-238 DECAY SERIES

	Half-life	Mode of decay[a]	Gamma energy (keV)[b]
^{238}U	4.468×10^9 a	Alpha	
^{234}Th	24.10 d	Beta	63.29 (4.8%), 92.38–92.8 (5.6%)
^{234m}Pa	1.17 min	Beta	1001.03 (0.837%)
^{234}U	245 700 a	Alpha	
^{230}Th	75 380 a	Alpha	
^{226}Ra	1600 a	Alpha	186.211 (3.59%)
^{222}Rn	3.8235 d	Alpha	
^{218}Po	3.10 min	Alpha	
^{214}Pb	26.8 min	Beta	351.932 (37.6%)
^{214}Bi	19.9 min	Beta	609.312 (46.1%), 1764.491 (15.30%)
^{214}Po	164.3 μs	Alpha	
^{210}Pb	22.20 a	Beta	46.539 (4.25%)
^{210}Bi	5.012 d	Beta	
^{210}Po	138.376 d	Alpha	
^{206}Pb	Stable	—	

[a] Only major modes of decay are shown.
[b] Only major gamma emissions of interest are shown.

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TABLE 45. THORIUM-232 DECAY SERIES

	Half-life	Mode of decay[a]	Gamma energy (keV)[b]
^{232}Th	1.405×10^{10} a	Alpha	
^{228}Ra	5.75 a	Beta	
^{228}Ac	6.15 h	Beta	911.204 (25.8%), 968.971 (15.8%)
^{228}Th	1.912 a	Alpha	
^{224}Ra	3.66 d	Alpha	240.986 (4.10%)
^{220}Rn	55.6 s	Alpha	
^{216}Po	0.145 s	Alpha	
^{212}Pb	10.64 h	Beta	238.632 (43.6%)
^{212}Bi	60.55 min	Beta 64.06% Alpha 35.94%	727.330 (6.67%)
^{212}Po	0.299 μs	Alpha	
^{208}Tl	3.053 min	Beta	583.191 (84.5%), 2614.533 (99.16%)
^{208}Pb	Stable	—	

[a] Only major modes of decay are shown.
[b] Only major gamma emissions of interest are shown.

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Appendix II

COMPOSITION OF PHOSPHATE ORES

Data on the composition of phosphate ores are given in Table 46 for the main chemical constituents, Table 47 for heavy metals and Table 48 for radionuclides. Some values have been rounded. The values reported are not necessarily representative of ores currently exploited. The ores are of sedimentary origin except where stated otherwise.

TABLE 46. MAIN CHEMICAL CONSTITUENTS OF PHOSPHATE ORES (BY COUNTRY)
(from Refs [298, 299] except where stated otherwise)

Country	Concentration (%)							
	P_2O_5	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	F	CO_2
Algeria	24–28							
Australia [300]	23							
Brazil[a]	8–34	24–45	11–30	0.1	2.8–8.4	2.4–3.5	1.6–2.6	
China:								
Guangxi[b]	8–16	14–24	40–54	0.3–0.5	7.4–11	3.1–5	0.9–1.3	0.4–1.7
Guizhou	22–36	52–53	3–4	2.5–3.5		1.5–1.8	3–4	
Hubei[c]	15–35	23	42	4.0	7.7	2.5	0.9	8.2
Hunan	<20–26							
Sichuan	17–28	7–39	4.1–5.7	0.15–0.7	4.7–28	2.1–8.4	0.3–2.5	0.8–1.8
Yunnan	24–32			0.6–0.7				
Egypt:								
Nile Valley	18–30	34–46	12–29	0.2–0.4	0.5–1.9	2.7–3.3	2.6	4.6–26
Red Sea	9.2–33	7.3–45	2–4.2	0.5–5.2		1.3–1.6	2.8–3.1	5.7–18
Abu Tartur[d]	29							
India [30]:								
Mussorie	15							
Cuddapah	0.5–28							
Karnataka	10–30							

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TABLE 46. MAIN CHEMICAL CONSTITUENTS OF PHOSPHATE ORES (BY COUNTRY) (cont.)
(from Refs [298, 299] except where stated otherwise)

Country	Concentration (%)							
	P_2O_5	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	F	CO_2
Israel	20–30							
Jordan	13–36	48 [301]	17–32 [301]					
Morocco	25–33; 22–28 [302]							
Russian Federation (Kola) (igneous)	4–31						1–3 [303]	
Senegal	15–39 [304]	8–47	12–45	0.8–5.2	0.5–32	0.5–10		
South Africa (igneous)	6–10 [304]							
Syrian Arab Republic	18–28							
Togo	26–30	41	9.4		10	2.1		
Tunisia	11–35							
Uganda (igneous)	30–40; 8–35 [304]	54	1.4		1.7	0.5	3.1; 1.5–4.4 [304]	
United Republic of Tanzania[e]	<20–30	44	4.2	2.1	1.4	0.9	2.9; ≤4 [304]	4.9
USA:								
Florida and North Carolina [305, 306]	9–14							
Idaho and Utah [305, 306]	22–24							
South Carolina	22							

[a] Na_2O: 0.2%; K_2O: 1%.
[b] Na_2O: 0.01–0.05%.
[c] K_2O: 3.8%.
[d] Rare earth elements: 0.2%.
[e] Na_2O: 0.5%.

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TABLE 47. HEAVY METALS IN PHOSPHATE ORES (BY COUNTRY)
(from Refs [298, 299] except where stated otherwise)

Country	Concentration (ppm)							
	Sr	Mn	Zn	Cd	V	Cr	Ba	Ti
Brazil		2600						
China:								
Guangxi					36–880			
Guizhou				10–30				
Hubei		14 000						
Sichuan	15 000–48 000				60–90			
Egypt (Nile Valley)			177	5	94	86		
South Africa (igneous) [307]								23 000–35 000
United Republic of Tanzania [304]	2500–9900						1100–2100	
USA (Idaho)					110–530	67–670		

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TABLE 48. RADIONUCLIDES IN PHOSPHATE ORES (BY COUNTRY)

Country	Activity concentration (Bq/g)						
	^{238}U	^{230}Th	^{226}Ra	^{232}Th	^{228}Ra	^{228}Th	^{40}K
China (Guangxhi) [298]	0.6–1.1						
Egypt (Nile Valley) [298]	0.7						
Morocco [304]	1						
Pakistan (Hazara) [51]			0.4			0.05	0.27
Russian Federation (Kola) (igneous) [15, 308]	0.07			0.1			0.1
South Africa (igneous)[a]	0.2		0.2	0.4		0.4	
Sudan [309]:							
Uru			4 (1.2–15)	0.01 (0.001–0.02)			0.06 (0.01–0.1)
Kurun			0.4 (0.15–0.8)	0.01 (0.002–0.02)			0.1 (0.06–0.36)
Syrian Arab Republic [52]	0.75–1.5						
United Republic of Tanzania [49, 310]	0.02–11	0.03–4.5	5.8	0.007–1.1	0.5	0.15–1.1	
USA:							
Central Florida [16, 46, 47, 311, 312]	0.75–3.1	1.3	0.7–3.1	0.02			0.003–0.019
Northern Florida [47]	0.06–0.1		0.2–0.5				
North Carolina [304]	0.6						

[a] Derived from values reported for phosphate rock (Appendix IV) and tailings (Table 8).

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Appendix III

PHOSPHATE-CONTAINING PRODUCTS AND THEIR APPLICATIONS

TABLE 49. FOOD AND PHARMACEUTICAL APPLICATIONS

Product and chemical formula	Application
Phosphoric acid	
Orthophosphoric acid, H_3PO_4 in H_2O	Acidulent in cola beverages; sugar refining; acid flavouring agent in jams and jellies; ingredient in bread dough and cake flour; yeast nutrient; cottage cheese production
Ammonium phosphates	
MAP, $NH_4H_2PO_4$	Buffer capacity; nutrient source; brewing
DAP, $(NH_4)_2HPO_4$	Buffer; nutrient source; dough strengthener; firming agent; processing aid; biscuits; brewing; sugar refining; ingredient in dentifrice
Calcium phosphates	
MCP, $Ca(H_2PO_4)_2$ or $Ca(H_2PO_4)_2 \cdot H_2O$	Anhydrous: Bakery applications, including self-raising flour, phosphated flour, self-raising corn meal, consumer prepared mixes and baking powder; calcium supplement in foods Monohydrate: Acidulent for foods and beverages; leavening acid; nutrient; dietary supplement; yeast food dough conditioner
DCP, $CaHPO_4$ or $CaHPO_4 \cdot 2H_2O$	Excipient for tableting; polishing ingredient in dentifrice; mineral, dietary and nutritional supplements Dihydrate: Nutrient; yeast food; leavening agent
Tricalcium phosphate, $Ca_5(OH)PO_4)_3$	Flow promoter for powders; suspension polymerization agent; nutritional mineral supplement; ingredient in dentifrice
Magnesium phosphates	
Magnesium phosphate, $MgHPO_4$, $MgHPO_4 \cdot 3H_2O$	Heat activated leavening agent; ingredient in baked goods including cakes, muffins, biscuits and pancakes
Dimagnesium phosphate, $MgHPO_4 \cdot 3H_2O$	Nutrient source; pH control agent; dietary supplement; flow aid

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TABLE 49. FOOD AND PHARMACEUTICAL APPLICATIONS (cont.)

Product and chemical formula	Application
Sodium phosphates	
Monosodium phosphate, NaH_2PO_4	Buffer and emulsifier in food preparation; acid ingredient in effervescent powders and laxatives; acidifier in non-cola beverages; buffers the pH of cheese and interacts with milk proteins to promote emulsification; gelling aid in desserts; prevents discoloration of mixtures of egg whites and yolks
Disodium phosphate, Na_2HPO_4 or $Na_2HPO_4 \cdot 2H_2O$	Anhydrous: Buffer; emulsifier or texturizer for instant puddings, evaporated milk, processed cheese, cereals, pre-cooked meats and pasta products; pharmaceuticals; water treatment in food processing Dihydrate: Emulsifier, especially for processed cheese; texturizer; buffer; nutritional mineral supplement
Trisodium phosphate, Na_3PO_4 or $4(Na_3PO_4 \cdot 12H_2O) \cdot NaOH$	Processed cheese and cheese products; quick cooking cereals; meat, poultry and cheese processing; post-chill antimicrobial treatment for raw poultry; clarifier in sugar mills
Sodium acid pyrophosphate, $Na_2H_2P_2O_7$	Leavening acid for baking powder; cake mixes; refrigerated or frozen dough and cake doughnuts; additive to non-dairy creamers; protects processed potatoes from iron induced darkening; decreases or prevents the formation of struvite crystals in albacore tuna; accelerates the development of a red colour in emulsion type meat products; emulsifying agent in cheese processing
Tetrasodium pyrophosphate, $Na_4P_2O_7$	Production of metal pyrophosphates; dispersant in malted milk powders; coagulant in instant puddings; colour and moisture retention in processed meats; prevents the formation of struvite crystals in canned seafoods and ice crystals in ice cream
Glassy sodium polyphosphates, sodium hexametaphosphates, $Na_{(n+2)}P_nO_{(3n+1)}$	Sequestration of multivalent ions to inhibit oxidative rancidity in food; water binding in cured meats and reduction of moisture loss during thawing and cooking of poultry and pork; emulsifies fat and protein; water treatment agent to prevent staining of the exterior of canned meat and poultry; scalding agent for meat and poultry; suspension agent in food
Sodium trimetaphosphate, $(NaPO_3)_3$	Food processing; starch modification; esterification of food starch; pharmaceuticals
Sodium aluminium phosphate, $Na_2Al_2H_{15}(PO_4)_8$	Heat triggered leavening acid used in bakery products such as refrigerated and frozen products; commercial baking powders and prepared mixes

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TABLE 49. FOOD AND PHARMACEUTICAL APPLICATIONS (cont.)

Product and chemical formula	Application
Potassium phosphates	
Dipotassium phosphate, K_2HPO_4	Nutrient for antibiotic production; pharmaceutical aid (buffering agent); emulsifier in non-dairy coffee creamers; cheese processing
Tripotassium phosphate, K_3PO_4	Emulsifier; alkaline buffer; pharmaceuticals
Potassium tripolyphosphate, $K_5P_3O_{10}$	Meat treatment for moisture binding; emulsifier and suspension agent in food
Phosphate blends	
Sodium acid pyrophosphate + calcium chloride, $Na_2H_2P_2O_7$, $CaCl_2$; l-ascorbic acid, $C_5H_8P_2O_7$; Citric acid, $C_3H_4(OH)(COOH)_3 \cdot H_2O$	Maintains the colour, texture and quality of fresh fruit and vegetables; increases the useful shelf life of most treated foods; delays the onset of oxidative and enzymatic browning
Disodium or trisodium phosphate + sodium metaphosphate, Na_2HPO_4 or Na_3PO_4, $(NaPO_3)_n$, n = 1000–5000	Emulsifying agent in pasteurized processed cheese; protein modifier; improves viscosity, melt spread, body and hardness
Sodium aluminium phosphate + MCP, $Na_3Al_2H_{15}(PO_4)_8$, $Ca(H_2PO_4)_2$ or $Ca(H_2PO_4)_2 \cdot H_2O$, $CaCO_3$, SiO_2	Anhydrous: Double acting leavening agent in self-raising flour, self-raising corn meal and biscuit mixes for a full volumed, light product Monohydrate: Acidulent and leavening agent in bakery applications such as pancakes, waffles, cakes and other prepared mixes; adding to the structure resiliency, crumb whiteness and baking tolerance of white cake mixes
Polyphosphate blends, $Na_5P_3O_{10}$ $Na_{(n+2)}P_nO_{(3n+1)}$, n = 10–16	Sequestration of multivalent metal ions to inhibit oxidative rancidity; reduces moisture loss during thawing and cooking; emulsifies fat and protein; improves solubility; improves gelation properties in surimi; gives a neutral pH and improves emulsion stability
Phosphorus chlorides and oxides	
Phosphorus trichloride, PCl_3	Intermediate in the manufacture of phosphate esters used in the production of several pharmaceuticals
Phosphorus pentachloride, PCl_5 and phosphorus oxychloride, $POCl_3$	Chlorinating agent used in the production of antibiotics
Phosphorus pentoxide, P_2O_5	Used in various organic synthesis reactions to produce intermediates for pharmaceuticals

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TABLE 50. INDUSTRIAL, AGRICULTURAL AND DOMESTIC APPLICATIONS

Product and chemical formula	Application
Phosphoric acid	
Orthophosphoric acid, H_3PO_4 in H_2O	Commercial grade: Manufacture of phosphates and fertilizers; acid cleaners; aluminium brighteners; metal phosphatizing; cement processing; leather tanning; fire bricks, silica bricks, crucibles and moulds; dental cements; opal glass and special glasses, such as that for sodium lamps; toilet preparations; varnish; synthetic rubber; boiler water treatment; potable water treatment Furnace grade: Semiconductor etchant; printed circuit board cleaner; reagent for analytical chemistry
Polyphosphoric acid, $H_{n+2}P_nO_{3n+1}$ Superphosphoric acid (mixture of ortho- and polyphosphoric acids)	Production of phosphates, phosphate esters; phosphorylation of polyols; metal cleaning and phosphatizing; aluminium brightening; electrolyte for fuel cells; refractory bonding; catalyst in organic reactions such as rearrangements, polymerization, dehydration, hydrolysis, nitration, bromination and cyclization
Ammonium phosphates	
MAP, $NH_4H_2PO_4$	Liquid and dry speciality fertilizer; fire and afterglow retardant; bonding agent in ceramics; corrosion inhibitors
DAP, $(NH_4)_2HPO_4$	Liquid and dry speciality fertilizer; fire and afterglow retardant; bonding agent in ceramics; corrosion inhibitors; welding of tin, copper, brass and zinc
Calcium phosphates	
MCP, $Ca(H_2PO_4)_2$ or $Ca(H_2PO_4)_2 \cdot H_2O$	Feed; fertilizer; opaque glass manufacture; paint preparations for steel enamels
DCP, $CaHPO_4$ or $CaHPO_4 \cdot 2H_2O$	Feed; mineral supplement; inner coating of fluorescent lamps; glass manufacture
Tricalcium phosphate, $Ca_5(PO_4)_3$	Feed; flow conditioning and anticaking agent; flow agent in dry powder fire extinguishers; additive to glues and resins in manufacture of plywood and granulated fertilizers; expandable polystyrene manufacture; fluorescent lamps; whitening of porcelain; enamels; glass manufacture

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TABLE 50. INDUSTRIAL, AGRICULTURAL AND DOMESTIC APPLICATIONS (cont.)

Product and chemical formula	Application
Sodium phosphates	
Monosodium phosphate, NaH_2PO_4	Metal cleaning and phosphatizing compounds; boiler water conditioning; dyeing of cotton; mineral supplement; buffer in electroplating; dairy cleaner to remove milkstones; feed supplement; shampoos
Disodium phosphate, Na_2HPO_4 or $Na_2HPO_4 \cdot 2H_2O$	Pigments; enamels; ceramics; detergents; welding Anhydrous: Boiler water conditioning; potable water treatment; phosphatizing metal cleaner; buffering agent in textile dye baths
Trisodium phosphate, Na_3PO_4 or $4(Na_3PO_4 \cdot 12H_2O) \cdot NaOH$	Anhydrous: Industrial and household cleaners; potable water treatment; bottle washing; textile washing; dyeing and bleaching; photographic film developer bath ingredient; builder and filler for soaps; paint remover; metal degreasing Dodecahydrate: Ingredient in alkaline cleaners to emulsify fats, greases and oils; buffering at high pH
Sodium acid pyrophosphate, $Na_2H_2P_2O_7$	Acid cleaners; metal polishes; oil well drilling muds; buffer; detergents; iron phosphatizing; dairy cleaner to remove milkstones; pigment dispersant in water based paints
Tetrasodium pyrophosphate, $Na_4P_2O_7$	Detergents and soaps; dispersant in clay processing; oil well drilling mud conditioner; water conditioning and textile processing; pitch control in paper mills; bleach bath stabilizer; alkaline metal cleaners; paper coating and filling; soil stabilization; manufacture of plastic granules for injection moulding
Glassy sodium polyphosphates, sodium hexametaphosphates, $Na_{(n+2)}P_nO_{(3n+1)}$	Industrial water treatment; potable water treatment; dispersion of pigmenting and dyeing operations in the textile industry; film development; oil well drilling mud deflocculant; sequestrant and suspension agent in clay processing; detergents; refractory binding
Sodium tripolyphosphate, $Na_5P_3O_{10}$ or $Na_5P_3O_{10} \cdot 6H_2O$	Anhydrous: Consumer and industrial cleaning products; detergents, such as for dishwashers, laundry and vehicle washing; potable water treatment; personal care products such as bath beads; clay slurry deflocculation; soil stabilization; cement manufacture; flotation reagent in mining; pitch control in wood pulping; textile operations Hexahydrate: Ingredient in compounds where rapid solubility or freedom from caking is essential; bath water conditioners
Sodium trimetaphosphate, $(NaPO_3)_3$	Consumer and industrial detergents and cleaning products; control of product density; dry bleach bases; phosphate detergent intermediate; potable water treatment

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TABLE 50. INDUSTRIAL, AGRICULTURAL AND DOMESTIC APPLICATIONS (cont.)

Product and chemical formula	Application
Potassium phosphates	
Monopotassium phosphate, KH_2PO_4	Seedbed fertilizer supplements; speciality and household fertilizers; nutrient for bacteria in biological waste treatment; potable water treatment; buffer capacity
Dipotassium phosphate, K_2HPO_4	Corrosion inhibitor in antifreeze; enamel production and paper processing; liquid fertilizers; potable water treatment; dispersion medium in liquid detergents
Tripotassium phosphate, K_3PO_4	Rubber processing; industrial and household cleaners; water conditioning; bottle washing; textile washing; dyeing and bleaching; photographic film developer bath ingredient; builder and filler for soaps; paint remover; metal degreasing
Potassium tripolyphosphate, $K_5P_3O_{10}$	Pigment dispersion in latex emulsion paints; sequestrant in liquid detergents; suspension agent; speciality boiler water compounds
Tetrapotassium pyrophosphate, $K_4P_2O_7$	Builder for liquid detergents and liquid potash soaps; synthetic rubber; buffer and sequestrant in electroplating baths; speciality boiler compounds; dispersant in water based paints; emulsifier of oils and greases; deflocculant in oil well drilling muds
Phosphate blends	
Sodium potassium polyphosphates	Builder for liquid consumer and industrial cleaning products
Phosphorus sulphides	
Phosphorus sesquisulphide, P_4S_3	Safety matches
Phosphorus pentasulphide, P_4S_{10}	Petroleum and lubricant additive intermediate; insecticide intermediate; ore flotation reagent; reaction with alcohols, mercaptans, amines and organic acids to produce thiophosphorus derivatives

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TABLE 50. INDUSTRIAL, AGRICULTURAL AND DOMESTIC APPLICATIONS (cont.)

Product and chemical formula	Application
Phosphorus chlorides and oxides	
Phosphorus trichloride, PCl_3	Intermediate in the manufacture of phosphate esters (used in plasticizers, hydraulic fluids, flame retardants and as a cryoscopy solvent), organophosphorus pesticides, organophosphines, phosphorus oxychloride, surfactants, stabilizers, defoamers and paper products; chlorinating agent; production of special metallic deposits
Phosphorus pentachloride, PCl_5	Chlorinating agent in the manufacture of dyes; catalyst for the condensation and cyclization reaction and to improve the grain structure of light-metal castings; production of materials by the agricultural industry; key ingredient in specialized fire retardants
Phosphorus oxychloride, $POCl_3$	Production of cosmetics and flame retardants
Phosphorus pentoxide, P_2O_5	Use in various organic synthesis reactions to produce intermediates for speciality chemicals; production of phosphate esters; drying agent (making use of its hygroscopic properties)

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Appendix IV

COMPOSITION OF PHOSPHATE ROCK

Data on the composition of phosphate rock are given in Table 51 for the main chemical constituents, Table 52 for heavy metals and Table 53 for radionuclides. Some values have been rounded. The values reported are not necessarily representative of current production. The phosphate rock is derived from ore of sedimentary origin except where stated otherwise.

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TABLE 51. MAIN CHEMICAL CONSTITUENTS OF PHOSPHATE ROCK (BY COUNTRY)

Country	Concentration (%)										Reference
	P_2O_5	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	F	CO_2	Na_2O	K_2O	
Algeria	29–31										[298, 305]
Australia	23										[305]
Brazil	35–36										[298]
China:											
Guizhou	28–36	45–52	3–10	0.7–2	1.3–1.8	1.3–1.8	4	5	0.5–1	0.5	[313]
Hubei	30–34	44–48	8	0.6–1.2	1.5a	1.5[a]					[314]
Sichuan	33	47	—	0.6	1.2	1.2	3		0.35	0.4	[315]
Egypt	29										[305]
India	30										[305]
Iraq	30										[305]
Israel	32–33										[298, 305]
Jordan	30–34										[301]
Morocco[b]	33–35	43–51	1.9–8.2	0.3–0.6	0.4–1.7	0.2–0.3	4	4.5	0.5–0.7	0.1–0.2	[144, 298, 316]
Russian Federation:											
Briansk	19–30										[305]
Kola (igneous)[c]	35–>40	51	1.1	0.1	0.4	0.3	3.3	0.2	0.4	0.5	[144, 298, 305]
Senegal	32–37	50	5	0.1	1.1	0.9	3.7	1.8	0.3	0.1	[144, 304]

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TABLE 51. MAIN CHEMICAL CONSTITUENTS OF PHOSPHATE ROCK (BY COUNTRY) (cont.)

Country	Concentration (%)										Reference
	P_2O_5	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	F	CO_2	Na_2O	K_2O	
South Africa (igneous)[d]	36–40	52–54	0.4–2.6	0.4–1.5	0.06–0.1	0.2–0.5	2.2–2.6	0.9–4.3	0.2	0.01–0.06	[48, 144, 304]
Syrian Arab Republic	30										[52, 305]
Togo	30–37	50–51	4.5–7	0.03–0.1	1	1–1.5	3.8–3.9	1.6	0.2	0.04–0.1	[144, 298, 304, 317]
Tunisia	30										[305]
Uganda (igneous)	40–42										[304]
USA:											
Florida[e]	27–34	50	3.7	0.3–1.25	1.1	1.1	3.9	3.1	0.5	0.1	[144, 318]
Idaho and Utah	27–29										[305, 306]

[a] Al_2O_3 and Fe_2O_3 concentrations assumed to be equal.
[b] Rare earth elements: 0.09%.
[c] Rare earth elements: 0.6%.
[d] Rare earth elements: 0.5%.
[e] Rare earth elements: 0.06%.

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TABLE 52. HEAVY METALS IN PHOSPHATE ROCK (BY COUNTRY)

Country	Concentration (ppm)										Reference
	Sr	Mn	Co	Ni	Zn	Cd	Hg	Cu	Pb	As	
Algeria	1800–2800	17–30	11	28	88–150	10–19	0.004	10–16	1.1–2.7	8	[319, 320]
China:											
Guizhou						3	5–6				[313]
Sichuan						0				80	[315]
Egypt (Abu Tartur)		1225	17	20	190	2.6–21		10	33	17	[319, 320]
Israel	120–2700	7–440	10	61–80	29–630	1.5–36	0.002	8–31	2.3–5.8		[319, 320]
Jordan	1100–2200	9–285	8.5–12	20–71	85–420	2.7–35		9–27	1–2.3	2.6–28	[319]
Morocco[a]	625–1000			35–44	155–400	<2–55	0.1	4–40	1–10	13	[144, 316, 320]
Russian Federation:											
Briansk					30	1			1.5	3.4	[319]
Kola (igneous)[b]	29 000–30 000	26	4	2–15	20–25	0.1–1.2	0.004–33	15–37	1.8	2–10	[144, 319, 320]
Senegal[c]						<5–115	0.2		5	18	[144, 304]
South Africa (igneous)	4500–4600	138–160	10	2–20	6–11	0.04–2	0.1–<0.2	90–200	11–18	8.7–13	[48, 144, 319, 320]
Syrian Arab Republic	1900	6–6.5	8	54–61	320–340	3.9–16		5–29	2–3.5	2.1–11	[319, 320]
Togo	1000	230				48–67	0.6			12	[144, 304, 315, 317]
Tunisia	4100	33	4.7	15	22–120	21–52		11	1.7–2	5.7	[319, 320]
Uganda (igneous)	4900	1350	90	100	290	0.25		33	9		[319]

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TABLE 52. HEAVY METALS IN PHOSPHATE ROCK (BY COUNTRY) (cont.)

Country	Concentration (ppm)										Reference
	Sr	Mn	Co	Ni	Zn	Cd	Hg	Cu	Pb	As	
USA:											
Florida[e]				28	70	6–10	0.02	13	17	11	[144, 320]
North Carolina						37–51					[320]

[a] Cr: 200 ppm; V: 160 ppm; Y: 50 ppm.
[b] Cr: 19 ppm.
[c] Cr: 6 ppm.
[d] Bi: <2 ppm; Cr: 1 ppm; V: 16 ppm.
[e] Cr: 60 ppm.

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TABLE 53. RADIONUCLIDES IN PHOSPHATE ROCK (BY COUNTRY)

Country	Activity concentration (Bq/g)								Reference
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	
Algeria	0.65–0.9		0.5–0.6			0.07–0.09			[48, 91]
Egypt (Nile Valley)	0.5		0.5			0.0004			[321]
Egypt	0.4–0.5		0.3–0.5			0.02–0.04			[311, 322]
India	1.34 (1.0–1.7)		1.32 (1.3–1.4)						[74]
Italy (Gela) [a]			1.24–1.25						[323]
Israel	1.5–2.6		1.5–1.8						[48]
Jordan	0.5–1.9		0.4–0.75	1		0.002–0.02			[48, 51, 91]
Morocco	1.34 (0.9–1.9)	1.5–2.0	0.9–2.0	0.7–1.9	1.7–1.9	0.007–0.03			[48, 74, 86, 98, 144, 308]
Russian Federation (Kola) (igneous) [b]	0.03–0.1		0.02–0.09			0.06–0.09			[48, 292, 293, 308]
Senegal	0.7–1.3		1–1.1	1					[48, 87, 144]
South Africa (igneous)	0.14 (0.11–0.18)		0.14 (0.11–0.16)	0.12 (0.10–0.13)		0.47 (0.33–0.61)	0.55 (0.40–0.62)	0.55 (0.45–0.61)	[48]
Togo	1–1.5		1.1–1.3	0.9		0.03–0.1	0.05	0.09	[48, 98, 308]
Tunisia	0.6		0.5–0.8			0.09–0.29			[48, 91, 308]

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TABLE 53. RADIONUCLIDES IN PHOSPHATE ROCK (BY COUNTRY) (cont.)

Country	Activity concentration (Bq/g)								Reference
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	
United Republic of Tanzania	4.1–4.6	4.7	5			0.6	0.7	0.6–1.3	[49]
USA:									
Florida	1.5		1.6–2						[292, 293, 324]
Central Florida:									
Pebble	1.3–2.5	2	1.6–3.6			0.03			[16, 47]
Concentrate	0.7–1.8	1.4	1–1.9			0.02			[16, 47]
Overall	1.4–1.5	1.6	1.5–1.6			0.02–0.03			[16, 308]
Northern Florida:									
Pebble	0.3–0.8		0.95–1						[47, 308]
Concentrate	0.1–0.2		0.6–0.8						[47]
Idaho	1.9		1.8			0.03			[308]
South Carolina	4.8–5		4.8–5			0.08			[48, 308]
Utah	1.6		1.9			0.03			[308]
Wyoming	2.3		2.3			0.01			[308]

[a] Pa-234m: 1.42–1.46 Bq/g; Pb-214: 1.23–1.26 Bq/g; Bi-214: 1.09–1.17 Bq/g; Pb-212, Bi-212: 0.04 Bq/g.
[b] K-40: 0.14 Bq/g.

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Appendix V

METHODS OF PHOSPHORIC ACID PRODUCTION USING SULPHURIC ACID DIGESTION

V.1. THE DIHYDRATE (DH) METHOD

The DH method is the most widely used of three so-called 'weak acid' methods. The acid digestion is carried out at a temperature of 70–85°C to yield phosphoric acid with a relatively low P_2O_5 content of 24–32% and dihydrate phosphogypsum crystals. A simplified schematic representation of the DH method is shown in Fig. 72.

In order to minimize the amount of unreacted rock remaining within the phosphogypsum, the particle sizes of the feedstock must lie within certain bounds. Some grades of commercial rock already meet this requirement, but most feedstocks require particle size reduction, usually using a ball mill or rod mill. In general, the degree of agitation and the amount of free sulphate in the attack tank determine the amount of milling required — a low free sulphate content and good agitation allows the use of coarser rock particles. Typically, the dihydrate process requires a feedstock particle size distribution in which 60–70% of the particles are less than about 100 μm. Traditional dry milling methods first require the moisture content of the rock to be reduced from 10–15% to, typically, 2%. The energy costs associated with this drying step have encouraged the industry to convert to wet milling, initially using fresh water but more recently making

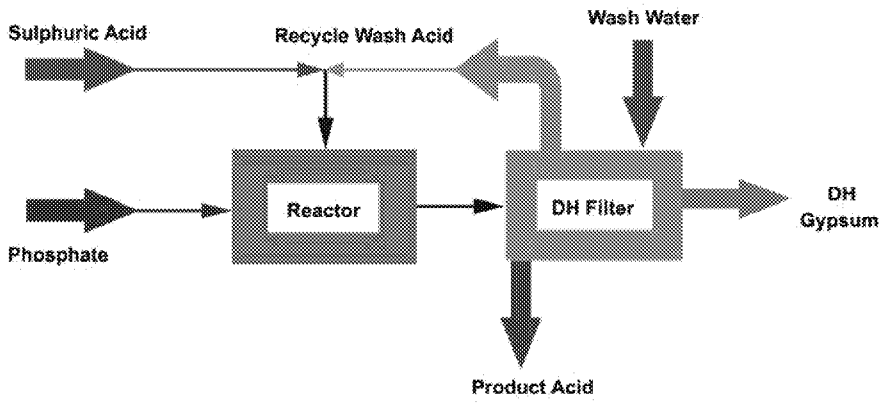

FIG. 72. The DH method [65].

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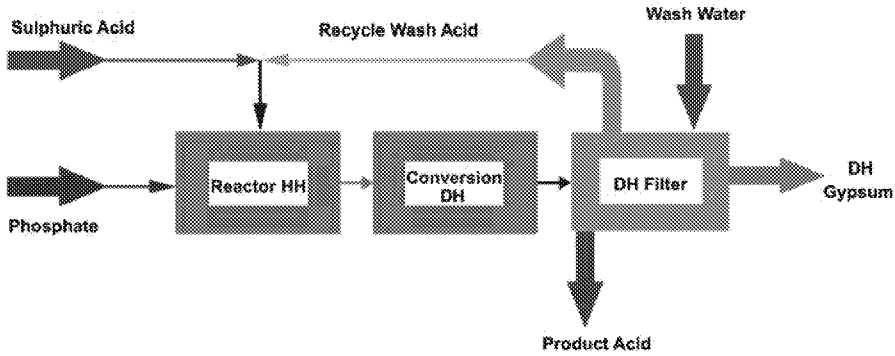

FIG. 73. The HRC method [65].

increased use of the partially neutralized acidic process water ('pond water') recycled from the phosphoric acid production process. In some facilities, the mill liners are manufactured from high alloy materials, allowing the use of 100% pond water without encountering corrosion problems. The use of pond water in this manner reduces the consumption of water and allows the recovery of P_2O_5.

Although a single attack tank is sometimes used, the reaction system more commonly comprises a series of separate tanks or tank compartments. The phosphogypsum crystals produced from the acid digestion process are separated from the phosphoric acid by vacuum filtration followed by up to four stages of countercurrent washing.

V.2. THE HEMIHYDRATE RECRYSTALLIZATION (HRC) METHOD

The HRC method, the second of the three weak acid methods, resembles that of the multiple reactor dihydrate process, except that the initial attack tank operates under hemihydrate conditions (for instance, at a temperature of 90–110°C). Subsequent attack tanks operate under conditions favouring the rehydration of the hemihydrate phosphogypsum to dihydrate phosphogypsum. The hemihydrate phosphogypsum is recrystallized to the dihydrate form without intermediate hemihydrate separation. The dihydrate crystals are then separated from the phosphoric acid by filtration, as described in Section 5.1.1.1. The method yields phosphoric acid with a P_2O_5 content of 30–32%, no better than that obtainable from the DH method (prior to concentration by evaporation), but the phosphogypsum has a higher level of purity. A simplified schematic representation of the method is shown in Fig. 73.

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In a variation of the HRC method, known as the 'repulping process', the phosphogypsum is converted back into a slurry and pumped to a second filtration step. The wash water from this second filtration step is returned to the first filtration where it is reused as the wash water for that step. Most of the free acid which is not removed in the first filtration step is removed in the second filtration step. Depending on the amount of free acid, the repulping process can improve the process efficiency by up to 2%. The residual P_2O_5 content of the phosphogypsum is reduced to only 2.5% [85].

V.3. THE DIHYDRATE–HEMIHYDRATE (DH/HH) METHOD

The DH/HH method is the third of the three weak acid methods. The phosphate rock feedstock is digested under dihydrate conditions and the phosphoric acid and dihydrate phosphogypsum are separated by filtration. However, the phosphogypsum crystals, rather than simply being washed at that stage, are instead converted to the hemihydrate form by heating with steam and additional sulphuric acid. The resulting hemihydrate phosphogypsum slurry is filtered and the liquor, containing residual P_2O_5, is returned to the initial dihydrate process step, thus avoiding the need for achieving a high degree of P_2O_5 recovery during the separation of the acid from the dihydrate phosphogypsum. The hemihydrate recrystallization stage operates at a P_2O_5 concentration of about 20–30% and a sulphuric acid concentration of 10–20%. The phosphoric acid product contains 32–36% P_2O_5. The P_2O_5 content of the phosphogypsum is only 1% [85]. A simplified schematic representation of the method is shown in Fig. 74.

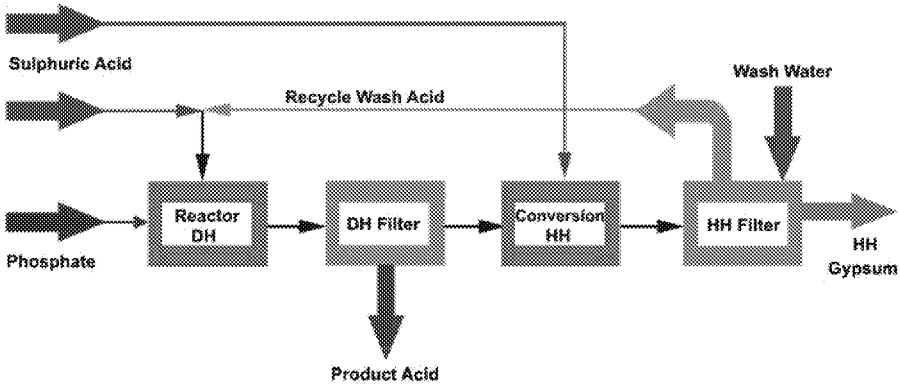

FIG. 74. The DH/HH method [65].

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V.4. THE HEMIHYDRATE (HH) PROCESS

The HH process is the first of two so-called 'strong acid' methods. The acid digestion conditions are controlled such that the phosphogypsum is precipitated in the hemihydrate form. The reaction temperature, for instance, is 90–110°C, higher than that used for dihydrate phosphogypsum production. Phosphoric acid with a P_2O_5 content of 36–52% is produced directly, resulting in significant energy and cost savings, in that the reaction vessels are similar to those used in the dihydrate method, but the need for prior particle size reduction is minimized or avoided. The P_2O_5 content of the phosphogypsum is relatively high (up to 8% [85]). A simplified schematic representation of the method is shown in Fig. 75.

V.5. THE HEMIDIHYDRATE (HDH) METHOD

The HDH method is the second of the two 'strong acid' methods. As with the HH method, the acid digestion conditions are such that the phosphogypsum is precipitated in the hemihydrate form. The hemihydrate crystals are then recrystallized to the dihydrate form and separated by filtration. The filtrate is returned to the process. The phosphoric acid product is removed by filtration at a strength of 42–45%, that is, similar to the values achievable with the HH method but in a narrower range. A simplified schematic representation of the method is shown in Fig. 76.

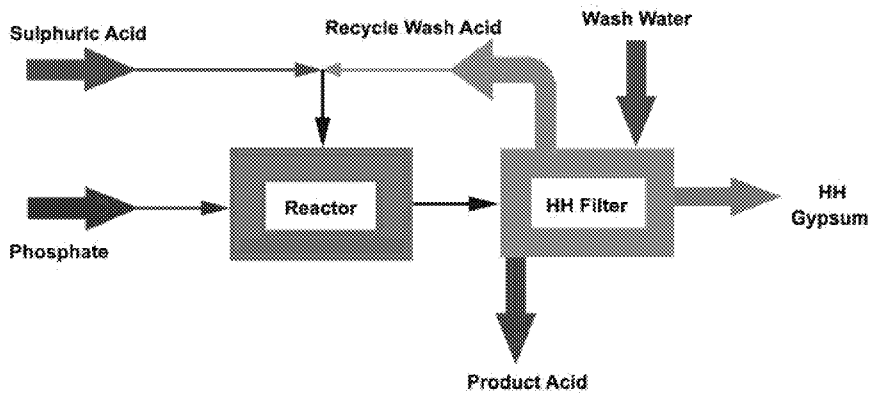

FIG. 75. The HH method [65].

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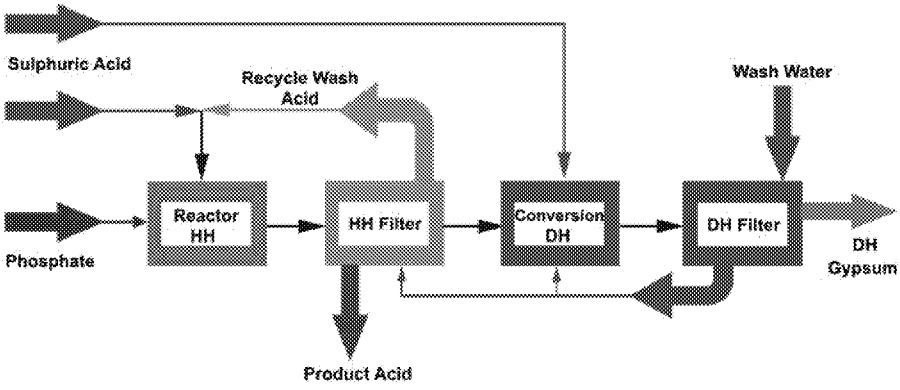

FIG. 76. The HDH method [65].

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Appendix VI

COMPOSITION OF PHOSPHOGYPSUM

Data on the compostion of phosphogypsum are given in Table 54 for the main chemical constituents, Table 55 for heavy metals and Table 56 for radionuclides. Some values have been rounded.

TABLE 54. MAIN CHEMICAL CONSTITUENTS OF PHOSPHOGYPSUM [48, 85, 133, 205, 209, 217, 325–330]

	Concentration (%)	
	Minimum	Maximum
CaO	24	34
SO_4	48	58
SiO_2	0.5	18
Na_2O	0.12	10
C (organic)	0.1	2.5
F	0.1	1.8
P_2O_5	0.05	8
Al_2O_3	0.05	0.6
Cl	0.035	0.045
MgO	0.01	0.54
Fe_2O_3	0.01	0.25

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TABLE 55. HEAVY METALS AND RARE EARTH ELEMENTS IN PHOSPHOGYPSUM [48, 74, 75, 77, 80, 137–139, 208, 219, 316, 325–327, 331, 332]

Element	Concentration (ppm)		
	Minimum	Maximum[a]	
Ti	26	470	
V	2	40	(190)
Cr	1.6	75	(594)
Mn	3.5	20	
Co	0.05	2.3	
Ni	1.7	250	
Cu	2	195	(508)
Zn	4	315	(351)
As	1.0	42	
Se	0.5	75	(249)
Sr	10	1118	(1606)
Y	2	156	
Zr	10	110[b]	(398)
Mo	1	16	
Ag	0.4	5	(73)
Cd	0.8[c]	40	
Ba	20	236	(810)
Hg	0.005	10	
Pb	0.5	16	(73)
Th	0.4	4	(75)
U	0.5	13.8	(19)
La	42	90	(419)
Ce	21	143	(425)
Nd	30	67	(352)
Sm	5	13	(60)
Eu	1.1	3	(15)
Yb	2.1	3.2	(21)
Lu	0.3	0.4	(2)

[a] Values in parentheses are maximum values reported for the fine fraction (<20 μm) [138, 139].
[b] A value of 700 ppm was reported for phosphogypsum of igneous origin [48].
[c] It is reported that, by adapting the parameters of the sulphuric acid digestion process, the cadmium concentration in the phosphogypsum can be reduced to less than 0.5 ppm, although this is offset by a higher cadmium concentration in the phosphoric acid [85].

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TABLE 56. RADIOACTIVITY IN PHOSPHOGYPSUM (BY COUNTRY)

Location of phospho-gypsum	Phosphate rock source		Activity concentration (Bq/g)								Reference
	Origin	Type	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	
Australia		Sedimentary	0.5		0.5			0.01			[333]
Belgium					0.44			<0.01			
Brazil	Brazil	Igneous			<0.004–0.67	0.05–0.89	0.05–0.68	0.01–0.18			[75]
Canada (Alberta)	Idaho	Sedimentary			0.9					0.01	[334]
Egypt	Egypt	Sedimentary	0.13		0.41			0.019			[50]
Finland					0.18			0.012			[50]
France			0.015		0.44			0.003			[50]
Germany		Sedimentary	—		0.60			<0.005			[50]
Hungary	Syrian Arab Republic	Sedimentary	—		1.1				0.07		[335]
India	Morocco	Sedimentary	0.17 (0.14–0.21)		0.82 (0.45–0.94)						[74]
Italy (Gela)[a]		Sedimentary			0.41–0.42						[323]
Netherlands		Sedimentary	0.05		0.9–1.25						[48, 87]
Nordic countries		Sedimentary			0.15–0.6	≤0.2	≤0.2	0.06			[48]
South Africa	South Africa	Igneous	0.07 (0.05–0.07)		0.11 (0.09–0.12)	<LLD[b]	<LLD	0.33 (0.13–0.59)	0.41 (0.35–0.5)	0.50 (0.24–0.63)	[48]
South Africa	Togo and South Africa	25% sedimentary 75% igneous	0.01–0.08		0.08–0.33	0.08–0.33	0.08–0.33	0.01–0.17	0.01–0.21	0.01–0.21	[48]

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TABLE 56. RADIOACTIVITY IN PHOSPHOGYPSUM (BY COUNTRY) (cont.)

Location of phospho-gypsum	Phosphate rock source		Activity concentration (Bq/g)								Reference
	Origin	Type	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	
Spain		Sedimentary	0.02–0.2		0.17–0.6	0.16–0.8	0.17–0.8	0.01–0.02			[48, 185]
Sweden	Russian Federation (Kola)	Igneous			0.02			0.06			[336]
United Republic of Tanzania	United Republic of Tanzania	Sedimentary	0.09	1.05	3.2			0.1		0.15	[49]
Tunisia (Sfax)	Tunisia (Sfax)		0.04–0.07		0.20–0.22			0.01–0.02			[219]
UK			0.13		0.63–0.78			0.01–0.02			[50]
USA (Florida)	Central Florida	Sedimentary	0.08–0.2	0.1–2.9	0.3–2.1	1.3–1.4	1–1.5	0.004–0.05		0.001	[16, 337–340]
USA (Florida)	Northern Florida	Sedimentary	0.005		0.50–0.55						[47]
USA			0.20		1.22–1.48			0.01			[50]
Former Yugoslavia		Sedimentary			0.4						[312]

[a] Pa-234m: <0.01–0.025; Pb-214: 0.29–0.31; Bi-214: 0.25–0.27; Pb-212, Bi-212: 0.02.
[b] LLD: lower limit of detection.

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Annex I

ASSESSMENT OF THE SOLUBILITY OF AIRBORNE DUST PARTICLES

I–1. INTRODUCTION

Radioactive particles deposited in the respiratory tract are removed by three main routes:

(i) Absorption into the blood;
(ii) Transport to the gastrointestinal tract;
(iii) Transport to regional lymph nodes.

Absorption into the blood involves the dissociation of particles and the uptake into blood of soluble substances and material dissociated from particles. The rate of particle dissolution in lung fluids is a crucial factor in determining the absorption rate. In the absence of specific data on absorption rates, default values are specified by the International Commission on Radiological Protection (ICRP) for the three general lung solubility classes of fast (F), medium (M) and slow (S) [I–1].

When conducting a dose assessment, the assignment of an appropriate solubility class tends to be based on conservative assumptions, leading to the likelihood of the dose being overestimated. This problem can be avoided by directly measuring the solubility of inhaled radioactive particles. In vivo measurements in humans are the most reliable source of data, but such data may be unavailable or insufficient, especially for the inhalation of airborne dust particles containing radionuclides of natural origin. As an alternative method, in vitro dissolution tests have been developed and used as research tools to estimate the solubility of particles. In the study reported in Ref. [I–2], and summarized in this annex, dissolution fractions and dissolution rates were determined for several key radionuclides of the ^{238}U decay series contained within airborne dust particles generated in phosphate fertilizer production plants. Measurements were made using a simulated lung fluid in an in vitro dissolution system.

I–2. ASSESSMENT METHOD

Samples of settled dust, aerosol particles and bulk products originating from the phosphate industry in central Florida, USA, were employed for solubility testing. Bulk products are produced via a dry granulation process using

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phosphoric acid as the feedstock. Dust originates from ungranulated products or small fragments of bulk products, which can be easily suspended as aerosols and subsequently settled. Since the granulator area is located inside a building, there is little possibility of airborne contaminants other than phosphate products. Therefore, the main components of the three types of dissolution test sample are likely to be similar. The sample materials comprised monoammonium phosphate (MAP) and diammonium phosphate (DAP).

The sizes of settled dust samples were found to be widely distributed, ranging from less than 1 μm to greater than 100 μm. The particle inhalability generally decreases with increasing particle size [I–1]. A typical upper size limit for suspended particles is 100 μm [I–3]. Large particles are seldom inhaled and, thus, contribute little to the committed effective dose. Therefore, the large particles were removed from settled dust with a 76 μm sieve prior to conducting the dissolution tests.

The particle size would be expected to influence the dissolution rate because of its relationship to the particle surface area — smaller particles would dissolve more rapidly than larger particles because a larger proportion of the particle mass is available for reaction by being close to the surface [I–4, I–5]. Samples of airborne particles smaller than 10 μm and samples of bulk products (MAP and DAP, with granule diameters of approximately 3 mm) were additionally tested for any potential size effect on particle solubility in the lung. The airborne dust samples were collected at the granulator area at two phosphate processing plants, using a PM_{10} high volume sampler (Sierra-Andersen, Model 1200) at a flow rate of 1130 L/min for 3 d. Particles collected on quartz fibre filters were mechanically detached for dissolution testing.

Various types of in vitro dissolution technique have been used in previous studies [I–4], including:

(i) Flow systems;
(ii) Static systems;
(iii) Batch methods.

The radionuclide mass concentration in phosphate particles is rather low. For example, the mass fraction of uranium in MAP and DAP ranges from 0.014 to 0.025% [I–6]. For dissolution techniques (i) and (ii), there is a lower limit on the applicable mass of target material. Therefore, dissolution technique (iii) — the batch method — was selected in order to increase the quantity of particles and, thus, increase the radionuclide concentrations in solution for analysis.

In previous studies [I–7, I–8], serum ultrafiltrate (SUF) had proved successful as a simulated lung fluid and was, therefore, chosen for this investigation. The SUF was prepared according to the procedures reported in those earlier studies and was

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used in conjunction with the batch method. Samples of material weighing 5 g were suspended in 200 mL of SUF in a flask, which was immersed in a water bath at a controlled temperature of 37°C. For the DAP samples, the pH of the stirred suspension was maintained within the range 7.3–7.4. For the MAP samples, the high fractional dissolution of the material caused the pH to decrease to 5.6–5.8 during the first day. After extracting the solution following that first day, the pH could subsequently be controlled within the range 7.3–7.4 by passing a mixture of 5% CO_2 and 95% air through the solution at a flow rate of 200–1000 mL/min. Leachate samples were collected initially after one day and periodically thereafter for a maximum of 50–85 d. To collect the leachate sample, the entire suspension was first passed through a 0.5 μm filter membrane. After separation of the dissolved fraction, the remaining undissolved particles were washed with 20 mL of SUF and the mixture passed through the same membrane. The filtrate was then passed through a 0.1 μm filter membrane. This double filtration method significantly reduced the possibility of leachate contamination by undissolved particles, which would have resulted in an overestimation of the dissolution rate. The double filtered leachate samples were reserved for subsequent analysis. The undissolved particles were resuspended in 200 mL of fresh SUF for the next leaching and filtration step.

The sample residues obtained from the dissolution tests were dissolved using a mixture of HF and HNO_3 [I–9]. Approximately 40 mg of residues were placed into Savillex screw-top Teflon vials and 0.5 mL of optima grade concentrated HF and 2.5 mL of optima grade concentrated HNO_3 were added. After placing the vials in an oven at 100°C for 24 h, the samples were evaporated to dryness on a hotplate. Then, 3 mL of optima grade concentrated HNO_3 doped with HCl were added to the samples, the vials heated on the hotplate for 24 h and then evaporated once again. The final residues were redissolved in 4 mL of 5% HNO_3 and diluted (about 2000 times) in preparation for analysis.

The solubilities of uranium, thorium and lead in the particles were characterized by measuring their isotope concentrations in the leachates and residues. The measurements were performed by high resolution inductively coupled plasma mass spectrometry (Thermo Electron Corp., Finnigan Element 2). The use of inductively coupled plasma mass spectrometry for health physics studies has increased in recent years owing to its high sensitivity and rapid procedure [I–10] to [I–13]. The intensities of the isotopes were measured at medium resolution. The measuring equipment was calibrated using gravimetrically prepared uranium, thorium and lead calibration standards. The greatest contributor to worker inhalation dose in the Florida phosphate industry is ^{230}Th, followed by ^{234}U and ^{238}U, respectively. Other radionuclides in the ^{238}U series make trivial contributions to worker doses owing to either their relatively low inhalation dose coefficients (^{234}Th and ^{210}Bi) or their low activity concentrations in MAP and DAP aerosol particles (^{226}Ra and ^{210}Po). Although the activity concentrations of ^{234}U,

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^{230}Th and ^{210}Pb in the SUF were comparable to that of ^{238}U, their mass concentrations were too low to measure by mass spectroscopy as their half-lives are short in comparison to that of ^{238}U. The mass concentrations in the SUF were highest for ^{238}U among the uranium isotopes, for ^{232}Th among the thorium isotopes, and for ^{208}Pb among the lead isotopes. Consequently, the solubilities of uranium, thorium and lead were determined from direct measurement of ^{238}U, ^{232}Th and ^{208}Pb.

Since SUF contains background levels of ^{232}Th, the concentrations of ^{232}Th in most leachate samples were below the detection limit — the mean, median, and maximum values of the detection limit were 0.89 ± 0.36, 1.03 and 1.15 mg/L, respectively. In such situations, the concentration of ^{232}Th was taken to be the maximum value of the detection limit. This conservative approach was taken in the light of the fact that an increased blood absorption of ^{230}Th will result in a corresponding increase in the worker effective dose.

The remaining mass fraction at each extraction time step was calculated using the following expression:

$$\text{Remaining fraction} = \frac{M_T - \sum_i M_i}{M_T} \qquad \text{(I–1)}$$

where M_T is the original mass of phosphate ions, ^{238}U, ^{232}Th or ^{208}Pb in the particle sample, and M_i is dissolved mass at each extraction. M_T was estimated as the sum of the cumulative masses measured in the leachate for all extraction steps and the final residual mass at the end of the dissolution test. Dissolution kinetics were expressed as the sum of two exponential functions as given in the lung clearance model described in Ref. [I–1]:

$$\text{Remaining fraction} = f_r e^{-s_r t} + f_s e^{-s_s t} \qquad \text{(I–2)}$$

where f_r and s_r are the dissolution fraction and rate constant for the rapid dissolution component, respectively, f_s and s_s are the corresponding values for the slow dissolution component, and t is the elapsed time [I–4]. Values of f_r, f_s and s_s were determined by means of a least squares analysis using SigmaPlot version 8.0 (SPSS, Inc.) [I–7]. Since the first leachate samples were collected only after one day, the solubility after shorter time periods (for instance, 10 min) was not directly measurable. The ICRP default value of 100 d^{-1} [I–1] was, thus, assigned as the rapid dissolution rate, s_r. A similar approach was adopted in Ref. [I–7].

It was postulated that the lung solubilities of radionuclides contained in the airborne particles of phosphate product are governed mainly by their chemical forms in the particles. The measurements showed that there was no statistically

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significant correlation between the dissolution rate and the product type or particle size. Since the majority of the surrounding phosphate matrix in the particle dissolved very rapidly, particle size did not appear to influence the solubility to any great extent.

I–3. RESULTS

The results of the investigation are shown in Fig. I–1. While the majority of the phosphate (the main component of the inhaled particle) dissolved rapidly in the simulated lung fluid, the dissolution of uranium, thorium and lead was generally less rapid. Between 3 and 14% of the ^{238}U in the particles dissolved rapidly in the simulated lung fluid, while the remaining fraction dissolved with a half-time of 91–315 d. The dissolution kinetics for ^{238}U were noted to be close to, but slightly slower than, those of materials in lung solubility class M in the lung clearance model described in Ref. [I–1]. For ^{232}Th, less than 1.4% of the radioactivity dissolved rapidly in the simulated lung fluid, with the remaining fraction dissolving with a half-time of more than 866 d. Solubility data for ^{208}Pb displayed a wide sample-to-sample variation. Between 3 and 41% of the ^{208}Pb dissolved rapidly, while the remainder dissolved more slowly with a half-time of 38–866 d. It was concluded that, for the purposes of radiation protection of workers in Florida phosphate processing plants, the data supported the selection of lung solubility class M for uranium and lead and class S for thorium.

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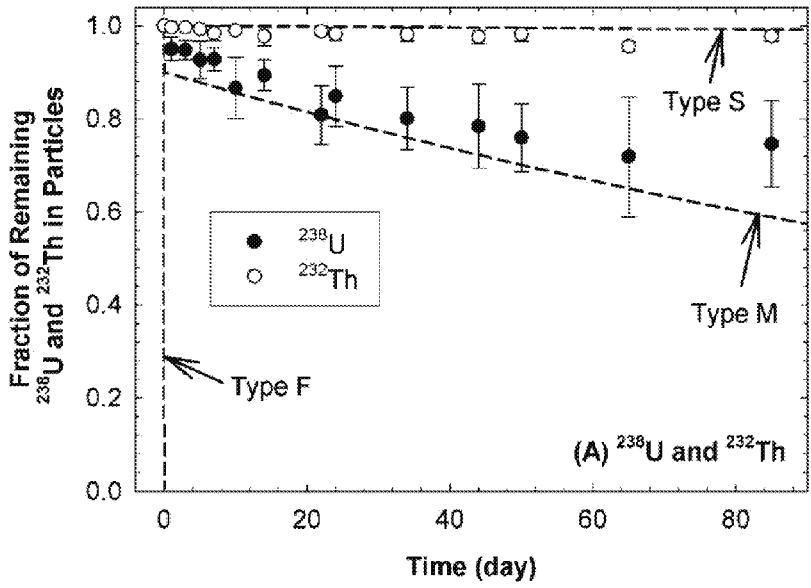

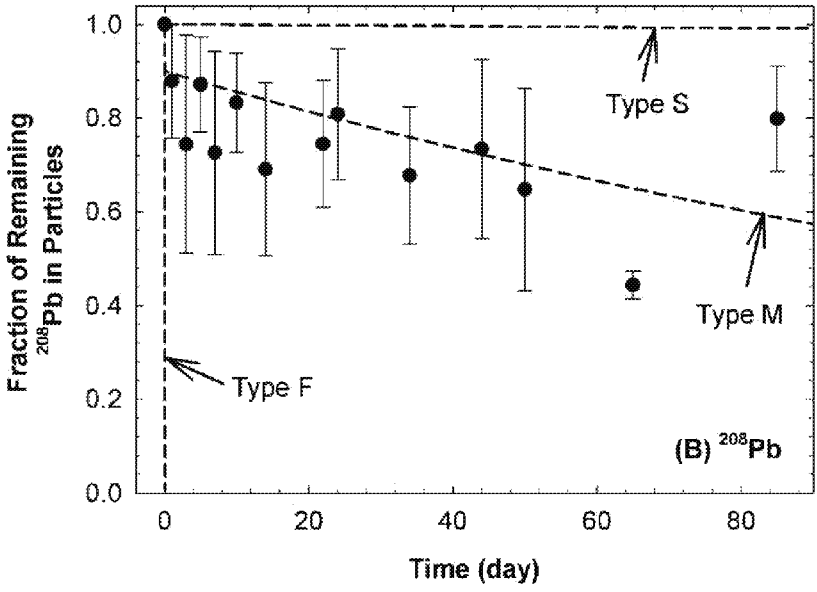

FIG I–1. Fractions of residual ^{238}U, ^{232}Th and ^{208}Pb in particles as a function of residence time in SUF simulated lung fluid. (A) ^{238}U and ^{232}Th; (B) ^{208}Pb. Residual fractions for lung solubility classes S, M and F given in Ref. [I–1] are shown for purposes of comparison.

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Annex II

REMEDIATION OF COASTAL AND MARINE PHOSPHATE RESIDUE DEPOSITS: THE TAPARURA PROJECT AT SFAX, TUNISIA

II–1. TUNISIAN PHOSPHATE DEPOSITS

Tunisia's phosphate deposits are found in the north-east of the country, as well as further south. Of these, the most significant are located in the Gafsa basin in the south-central region. In 2010, the Compagnie des Phosphates de Gafsa produced 7.6 million t of phosphate rock from seven open-pit mines and one underground mine, making Tunisia the world's fifth largest producer. Phosphate rock and phosphate products (phosphoric acid, triple superphosphate (TSP), diammonium phosphate (DAP) and dicalcium phosphate (DCP)) together comprise Tunisia's primary export and are sold to 50 countries in five continents.

II–2. MINING AND PRODUCTION

Compagnie des Phosphates de Gafsa supplies approximately 80% of its phosphate rock production to the Groupe Chimique Tunisien, which operates several phosphoric acid plants. The remaining 20% of its production is exported through the port of Sfax. Groupe Chimique Tunisien has the capacity to produce more than 700 000 t/a of phosphoric acid, 1 million t/a of TSP, 600 000 t/a of DAP, 300 000 t/a of nitrogen-phosphate-potash and 100 000 t/a of monoammonium phosphate (MAP).

Groupe Chimique Tunisien owns four industrial production centres located in Sfax and M'dhilla (for TSP), Gabès (for phosphoric acid, DAP and DCP) and Skhira (for phosphoric acid). Approximately 800 000 t of TSP is produced annually at the Sfax and M'dhilla sites.

II–3. PHOSPHATE INDUSTRY ACTIVITIES AT THE CITY OF SFAX

The city of Sfax is located on the Gulf of Gabès, 270 km southeast of Tunis, and has a population of 340 000 (2005). It is the capital of the Sfax Governorate and is a leading centre of industry and commerce. Sfax is the largest port in Tunisia, handling the export of both phosphate rock and phosphate products.

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Rock for export is transported by rail to the docks from the Metlaoui and Jebel M'dhilla mining areas.

The Sfax plant, which commenced production in 1952, was the first phosphate rock processing facility in Tunisia. It was also the birthplace of the multi-tank processing technology known as SIAPE, named after the company Société Industrielle d'Acide Phosphorique et d'Engrais that first developed it. SIAPE is now part of Groupe Chimique Tunisien. This method was designed to handle low grade phosphate ores. It was implemented at the phosphoric acid and TSP plants in Gabes, M'dhilla and Skhira.

The Sfax harbour facility was the location of an industrial area which included a phosphate plant that commenced operation in 1964. Phosphogypsum and other residues were discharged directly on to the beaches and into shallow offshore areas (the latter being, in effect, a 'dilute and disperse' management option), resulting in the accumulation of a large, square phosphogypsum stack close to the harbour and town (see Figs II–1 and II–2). As the stack increased in size, protective sea walls were constructed to confine the material and prevent erosion. The phosphogypsum residue contained low levels of metals, such as cadmium, arsenic and nickel, as well as radionuclides of the uranium decay series and, to a lesser extent, the thorium decay series. The average ^{238}U and ^{226}Ra concentrations in the Sfax phosphogypsum residues are at the lower end of the ranges reported worldwide. The ^{226}Ra activity concentration is approximately 0.4 Bq/g. The beaches were closed and swimming was forbidden in 1978 owing to the pollution arising from the phosphogypsum stack. The plant itself was closed in 1991. The stack, which covered an area of approximately 50 ha and reached a height of up to 8 m above sea level, was surrounded by a crusty layer of phosphogypsum ('plaque') with an area of 90 ha and a depth of up to 3 m.

Public exposure from operating phosphoric acid and fertilizer plants can occur through the inhalation of radon gas released from phosphogypsum stacks and through the migration of radionuclides into groundwater and surface water bodies, including the sea. Previous studies [II–1, II–2] have shown that the discharge of phosphogypsum into surface water bodies can result in significantly elevated levels of radionuclides, such as ^{210}Po in water, sediments and biota. Exposures are estimated to be in the range 2–10 μSv/a [II–3], with maximum values of up to 150 μSv/a [II–4]. The highest values occur where there are discharges to marine water and freshwater, resulting in the contamination of fish and shellfish used as local foodstuffs.

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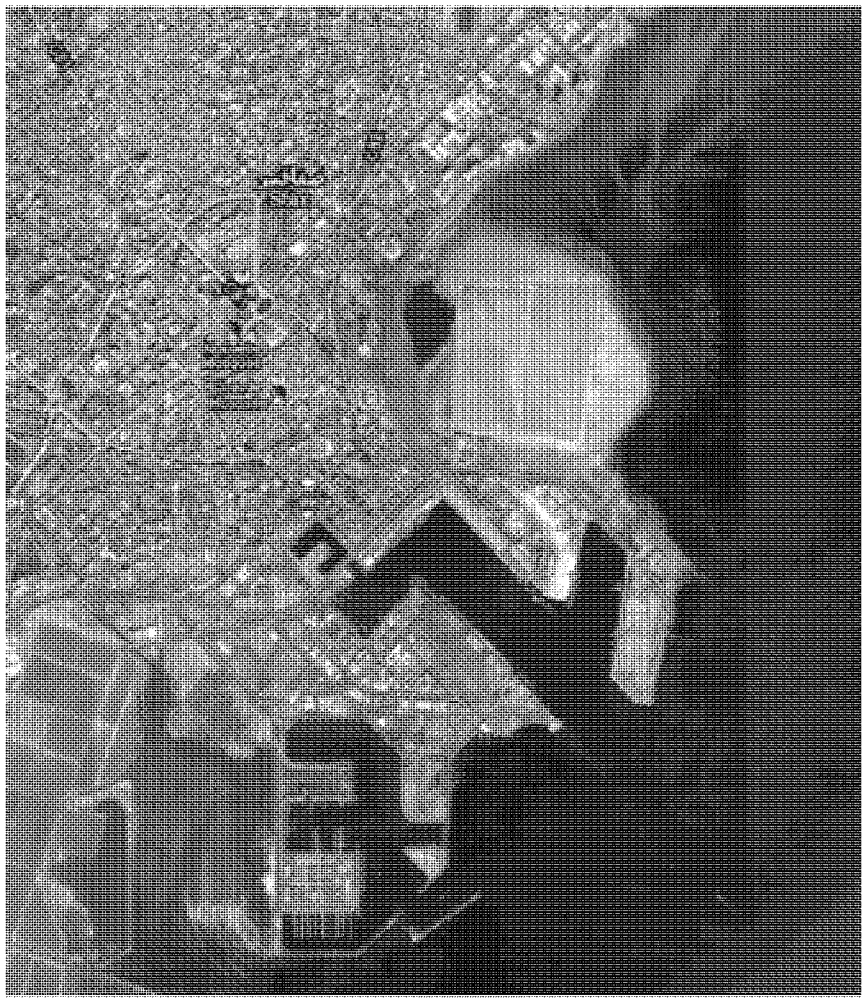

FIG. II–1. Satellite image of the Sfax phosphogypsum stack, harbour and town before the start of remediation work.

II–4. OBJECTIVE OF THE REMEDIATION PROJECT

The Taparura project at the Sfax site was divided into two main phases:

(i) Identification and remediation of the contaminated areas and recovery of land from the sea;
(ii) Development of the area and construction of a new urban centre.

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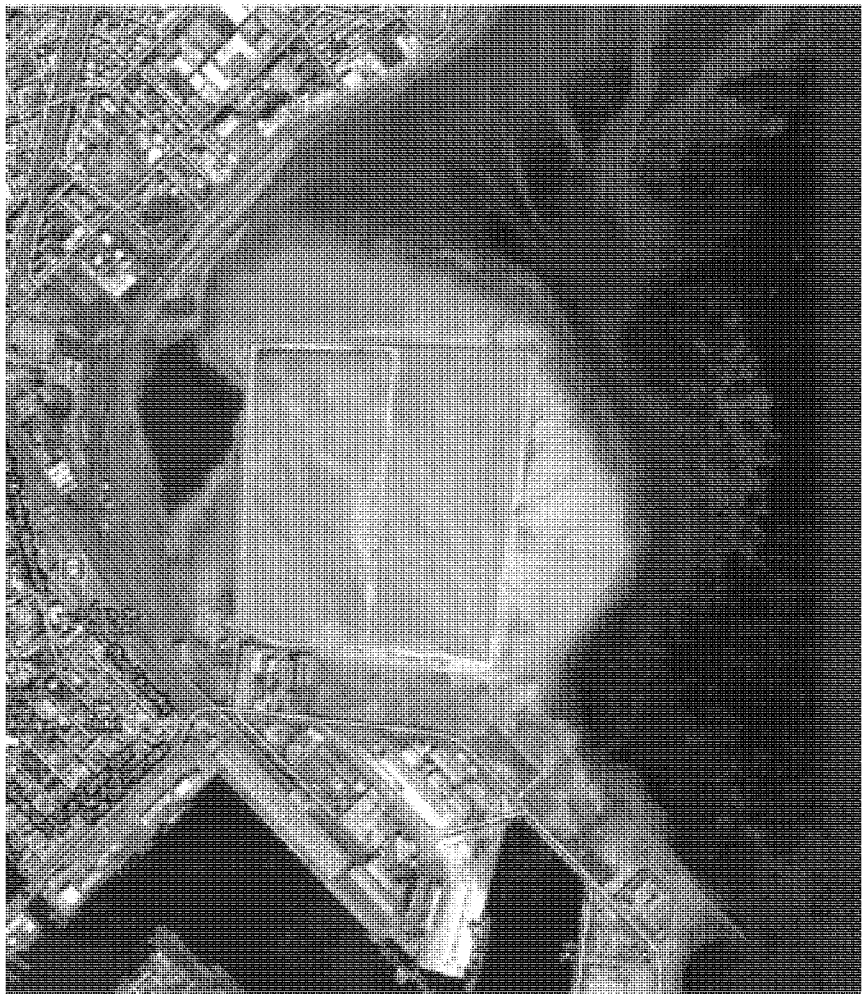

FIG. II–2. Enlarged view of the Sfax phosphogypsum stack before the start of remediation work.

The project was initiated to remove the contaminated materials on the land and in the sea, to consolidate these residues into a designed central containment, to restore the beach facilities close to the town and to reclaim additional land from the sea for urban expansion and tourism. Remediation work on the project began in April 2006 and was carried out over a period of 28 months. The first project phase, involving the removal of contaminated material from the sea and on land, was completed by 2008. The recovered contaminated material was consolidated into an engineered structure and a cover layer was subsequently

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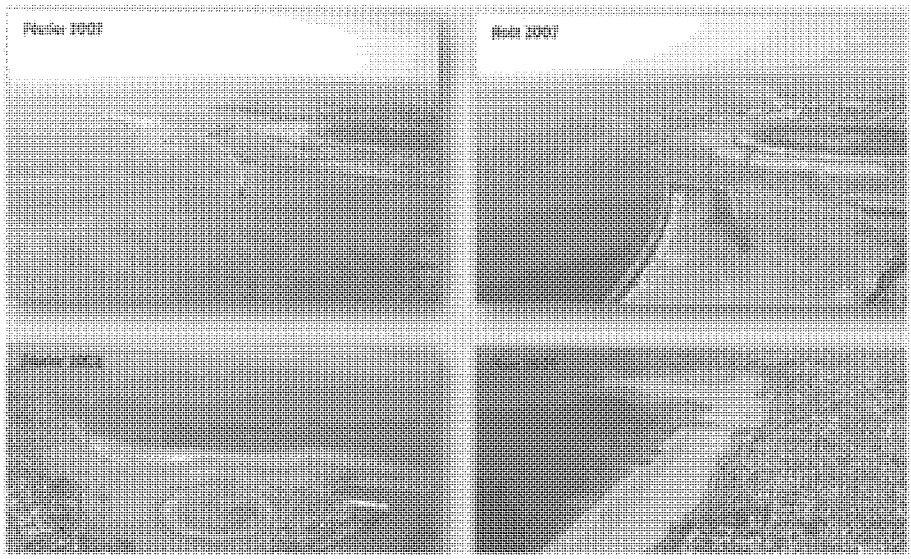

FIG. II–3. Various stages of progress with the remediation project.

added. Revegetation of the cover layer began in 2009. The project entered a two year guarantee period in June 2009, during which the remediated area was inspected and evaluated, with a variety of monitoring programmes (including radiation monitoring) being implemented. Aerial views of the site at various stages of project implementation are shown in Fig. II–3.

II–5. PROJECT MANAGEMENT

Project management was carried out by an autonomous government company Société d'Études et d'Aménagement des Côtes Nord de la Ville de Sfax under the supervision of the Ministry for Infrastructure and Housing. The work of the project was performed by a consortium of specialist companies from Belgium, France, Netherlands and Tunisia. The project, which cost €75 million, was funded through taxes and through loans from the European Investment Bank and financial institutions in Belgium and France.

II–6. DEVELOPMENT OF THE REMEDIATION PLAN

Several comprehensive studies were carried out to characterize the site and to determine the extent of the polluted areas and the quantities of materials to be

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remediated and contained on-site [II–5 to II–7]. The polluted area was assessed on the land and in the shallow sea surrounding the phosphogypsum stack. The monitoring focused on a number of key heavy metals (nickel, copper, cadmium, lead and chromium) and arsenic. The pollutant reference levels used to define the area requiring remediation were derived from Dutch standards on environmental remediation and were related to ecological risk criteria.

Once the extent of the polluted areas and the quantities of contaminants had been defined, the project engineers investigated the remediation options and the technologies required to complete the project. A clear priority was to minimize the contaminated area, which required the removal of significant quantities of solids from land and sea. Another priority was the long term physical stability of the containment and the design technology required to minimize the transport of pollutants from the containment into the surrounding groundwater. The design studies considered a number of long term aspects, such as the physical integrity of the structure and the site, hydrological aspects, the potential for floods and coastal erosion.

The option selected involved excavating the contaminated material (from both land and sea) and, after dewatering, incorporating it into the original phosphogypsum stack. Work carried out on the stack included the reshaping of the slopes, the installation of a vertical barrier around the perimeter in order to create a stable confined area, the installation of a cover layer of uncontaminated sand and the application of a new topsoil layer.

II–7. MOVEMENT OF MATERIAL

Approximately 1.7 million m^3 of various materials were excavated on land, including approximately 1.25 million m^3 of phosphogypsum plaque that surrounded the original stack. The modification of the stack shape from a square to a circular geometry involved the movement of 0.787 million m^3 of material, while a further 0.465 million m^3 of contaminated sediment was dredged from the sea and incorporated into the stack. The use of specialized computer controlled geographic information system positioning technology was required to dredge the polluted material from the sea. The polluted materials were sampled before and after dredging to ensure that the required level of decontamination had been achieved. The wet polluted material was stockpiled and dewatered in a specially designated area on top of the existing stack.

Backfilling of the remediated areas and the creation of a new beach entailed the movement of approximately 8 million m^3 of material. It was necessary to dredge approximately 7 million t of sand from an unpolluted area approximately 20 km from the site using trailer suction hopper dredges. Coastal protection was

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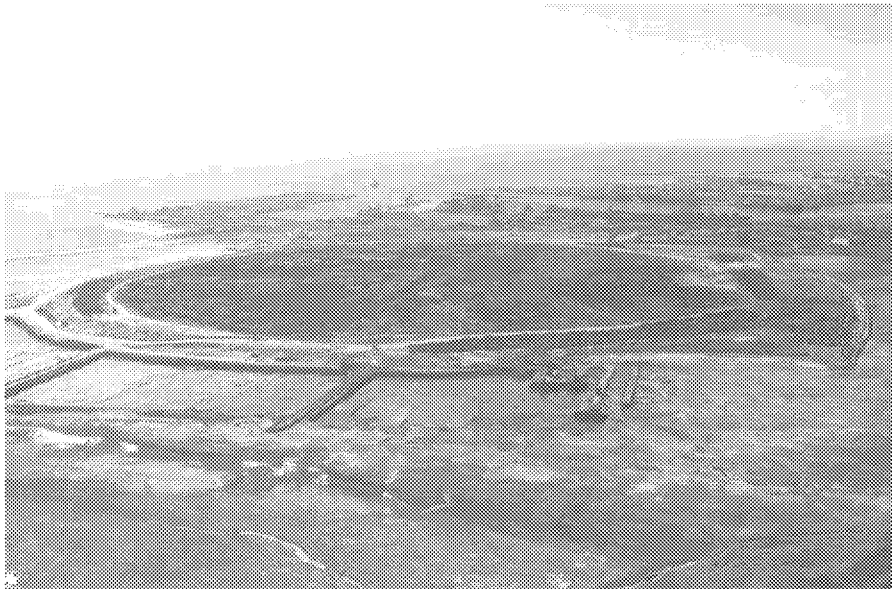

FIG. II–4. View of the site during the relocation of the plaque layers to the remediated stack.

enhanced by the construction of seven breakwaters around the site. The remediated site and containment were further protected by the construction of ring dykes and flood channels (requiring the excavation of approximately 0.45 million m^3 of material) to provide for flood control, to enable the dewatering of the consolidated phosphogypsum and to provide access to the remediated site.

Various activities involved in the movement of material are shown in Figs II–4 to II–7.

II–8. THE REMEDIATED STACK

The rectangular phosphogypsum stack was converted into a circular, terraced structure with a diameter of approximately 0.9 km, an area of 55 ha, a maximum height of 16 m and a 1 in 5 slope (see Fig. II–8). A layer of uncontaminated soil excavated from a site 20 km from Sfax was used to cap the 4 million t of material contained within the structure. The soil thickness varied from 0.8 m (on the top and terraces) to 2 m on the slopes. The design studies and modelling carried out prior to remediation indicated that a minimum thickness of 30 cm of uncontaminated cover was required to attenuate adequately the radon gas and gamma radiation emitted from the contained material. This criterion was

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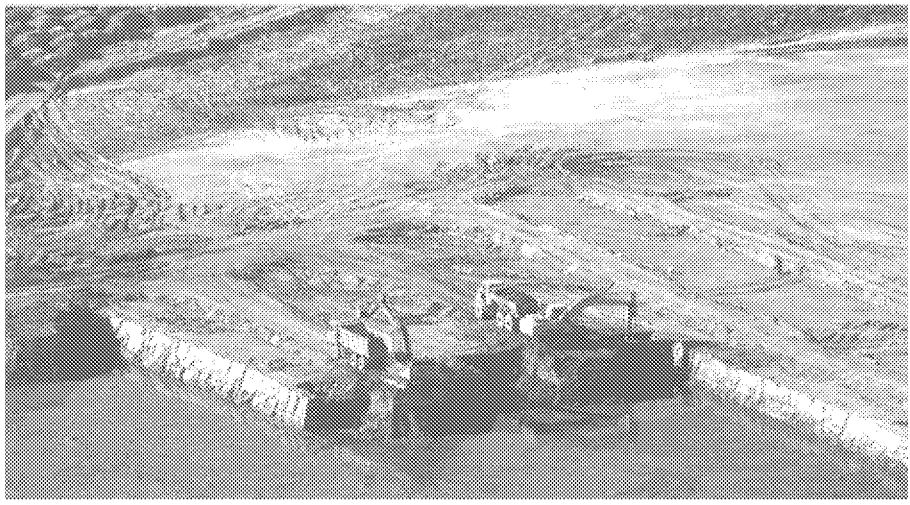

FIG. II–5. Removal of the plaque layers.

FIG. II–6. View of the site during the backfilling of the rehabilitated areas with uncontaminated sand.

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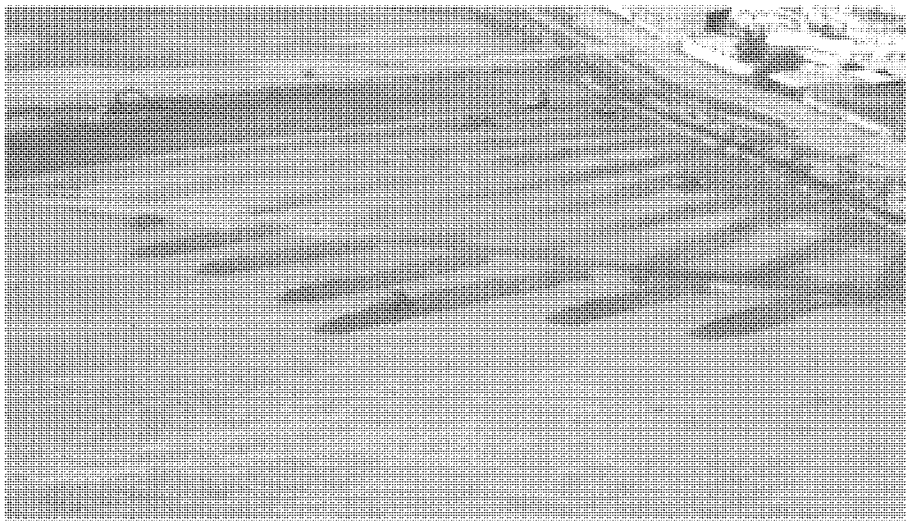

FIG. II–7. Backfilling of the rehabilitated areas with uncontaminated sand.

FIG. II–8. Aerial view of the remediated site, with the remediated stack visible in the centre.

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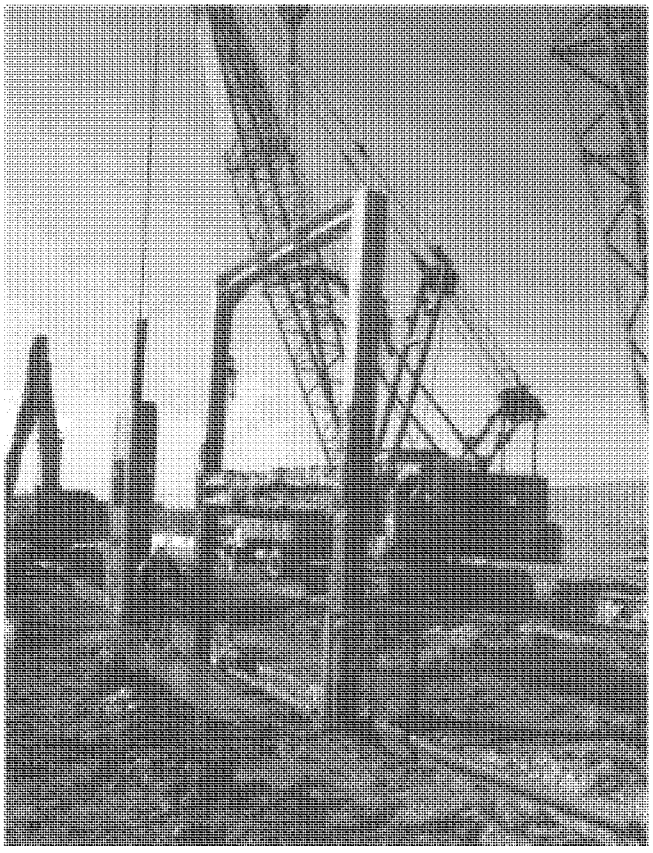

FIG. II–9. Construction of the concrete–HDPE water barrier around the remediated stack.

based on the assumption that permanent structures such as housing or offices would not be constructed on the top of the remediated stack.

The remediated stack is underlain by a sandy silt layer (the original beach). Beneath this, 7–9 m below the ground surface, is a thick layer of natural, consolidated red clay. The stack is surrounded by a barrier comprising vertical, interlocking, 3 mm thick high density polyethylene (HDPE) panels embedded in a bentonite and concrete foundation 2.8 km long, 0.6 m wide and 12 m deep (see Figs II–9 to II–11). This barrier prevents the lateral movement of polluted water from the remediated stack into the surrounding groundwater. The foundation of the circular barrier is embedded in the natural red clay layer to a depth of 2.5 m. The groundwater levels on either side of the lateral barrier are automatically monitored. The design of the remediated stack includes a number of boreholes for sampling and for measurement of groundwater levels.

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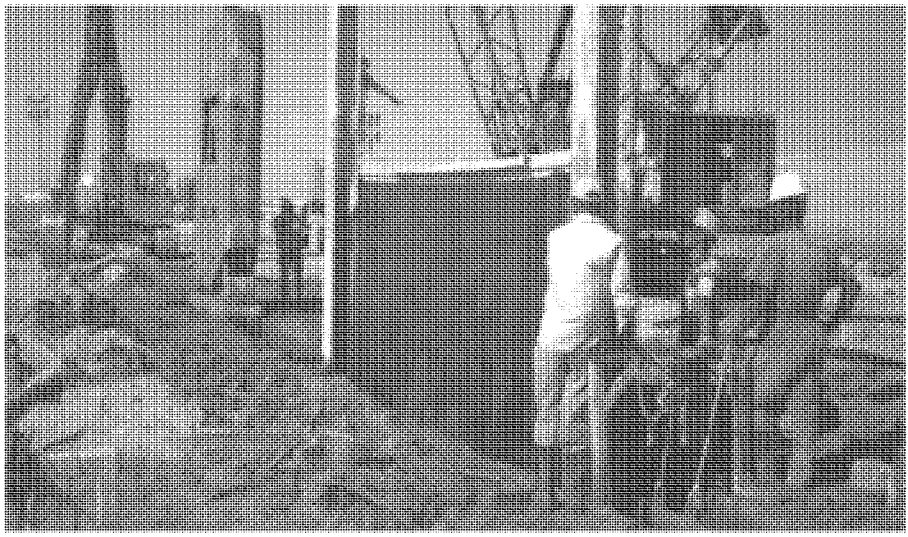

FIG. II–10. Construction of the concrete–HDPE water barrier around the remediated stack.

FIG. II–11. The base of the remediated stack, with the concrete–HDPE water barrier visible in the foreground.

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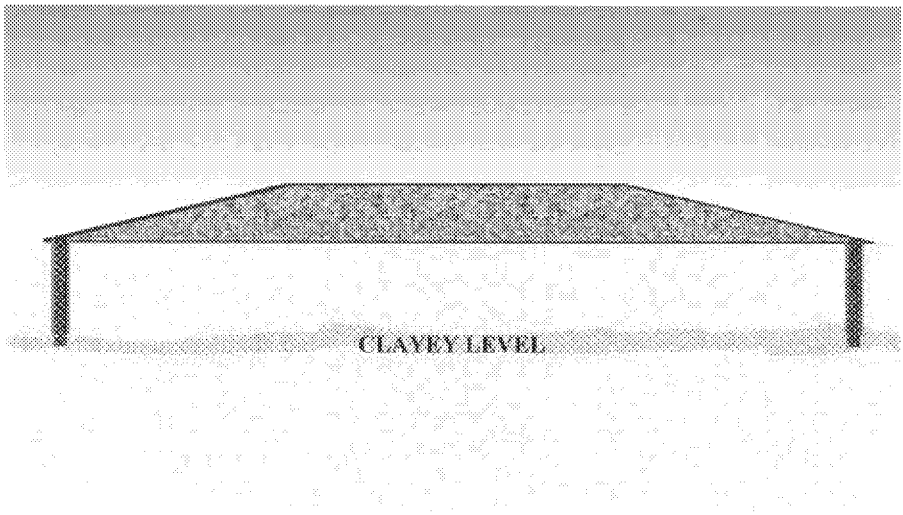

FIG. II–12. Simplified profile of the remediated stack, showing the underlying clay layer.

II–9. CONTROL OF SEEPAGE WATER

The clay layer beneath the remediated stack (see Fig. II–12) retards the downward movement of seepage water and purifies it by retaining a significant fraction of the heavy metal and radionuclide contents. The project engineers have estimated that the thickness of the clay is sufficient for this purification process to continue for several thousands of years.

The groundwater level below the remediated stack is constantly monitored by automatic systems. Water is pumped out automatically whenever the level approaches a height of 10 cm below that of the groundwater outside the water barrier. Seepage water beneath the remediated stack is collected and pumped through pipes into the flood control channel which then discharges into the harbour.

Prior to the remediation process (1994–1998), the seepage water had a high degree of acidity (pH4). Subsequently, the pH value rose towards neutrality and is now neutral. Analysis of the seepage water indicates that it contains elevated concentrations of phosphate and nitrate but very low levels of metal pollution.

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FIG. II–13. Stormwater channel.

II–10. CONTROL OF THE QUALITY OF SURFACE WATER AND GROUNDWATER

The average annual precipitation in the area is approximately 250 mm and from time to time the Sfax area is subject to intense rainfall. In 1984 there was a 1 in 100 year storm resulting in severe flooding of the area. This impact was considered in the design of the project and the flood control canals were built to protect the remediated area and handle the large amount of surface runoff water anticipated from this type of event. The surface runoff is collected and directed into the flood control channel which discharges into the harbour (see Fig. II–13).

II–11. FINAL OUTCOME OF THE PROJECT

Up to 2011, 6 km of coastline had been restored. The project involved the creation of 6 km of beach and 420 ha of land for urban development (260 ha of remediated land and 160 ha of land recovered from the sea). The beach and landfill restorations have provided space for new recreational activities (e.g. beaches, parks and sports grounds), an educational, health and museum infrastructure and social housing programmes. Monitoring of the remediated areas will continue.

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II–12. COMMUNICATION WITH THE PUBLIC

Communication with the public and stakeholder groups (e.g. individuals, community groups, regulatory bodies, universities and news media) was addressed at all stages of the project through a variety of mechanisms such as meetings, workshops, the internet, brochures and media communications. Throughout the project, the Centre Nationale de Radioprotection played a prominent role in addressing concerns about radiation issues.

II–13. RADIOLOGICAL SURVEYS AND ASSESSMENTS

The goal of remediation activities, such as those conducted as part of the Taparura project, is the timely and progressive reduction of the hazard and, eventually, if possible, the removal of regulatory control from the area without restrictions on future use [II–8, II–9]. In terms of IAEA safety standards, the remediation process should:

(a) Reduce the doses received by exposed individuals or groups of individuals;
(b) Avert doses to individuals or groups of individuals that are likely to arise in the future;
(c) Prevent or reduce environmental impacts from the radionuclides present in the contaminated area.

Reductions in the doses received by individuals and the amelioration of environmental impacts can be achieved by actions applied to the source of contamination (e.g. isolation) or by actions to remove the source, to modify the exposure pathways or to reduce the numbers of individuals or other receptors exposed to radiation from the source.

From 1998 onwards, several comprehensive radiological surveys were carried out prior to, during and after the rehabilitation work to assess occupational and public exposures [II–10] to [II–16]. In addition, gamma radiation surveys were conducted to identify and to assess the contaminated areas. The surveys were conducted using portable instruments, fixed monitoring stations and integrating devices (thermoluminescent dosimeters and track etch devices) for gamma radiation, indoor and outdoor radon, radon progeny and airborne dust. After evaluation of the initial radiological assessments, the Centre Nationale de Radioprotection defined a level of public exposure of less than 1 mSv/a above background levels for the future use of the remediated site, which was in line with international recommendations and standards at that time [II–17] to [II–19].

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The radiological assessments have demonstrated that, through the Taparura project, a reduction in the doses received by members of the public has been achieved by concentrating and containing the phosphogypsum residue in a central containment and backfilling the remediated areas with uncontaminated materials. The source is now confined to a small area of the site and the design of the remediated stack ensures that the migration of radioactivity into the environment remains within acceptable levels.

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Poffijn, A.	Federal Agency for Nuclear Control, Belgium

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Consultants Meetings

Vienna, Austria: 11–15 November 2002, 15–19 November 2004, 9–10 February 2006, 17–28 July 2006, 30 August–8 September 2006, 6–8 November 2006, 27 November–1 December 2006, 18–19 December 2007, 23–25 February 2011

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Safety Reports Series No. 76
STI/PUB/1568 (105 pp.; 2012)
ISBN 978–92–0–132110–7 Price: €32.00

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This Safety Report is a compilation of detailed information on the processes and materials used in the phosphate industry and on the radiological considerations that need to be taken into account by the regulatory body when determining the nature and extent of radiation protection measures. It has been developed as part of the IAEA's programme on the application of its safety standards in the fields of radiation, transport and waste safety. The information provided will assist in the implementation of a graded approach to regulation. This Safety Report provides information on expected radionuclide concentrations, exposure levels and the most appropriate regulatory approach for the phosphate industry, including mining and beneficiation of phosphate ore, phosphoric acid production, phosphogypsum and the utilization of rare earth phosphate residues.

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ISBN 978–92–0–135810–3
ISSN 1020–6450

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Message

From: Wieder, Jessica [Wieder.Jessica@epa.gov]
Sent: 8/12/2020 12:24:02 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: Re: For Review | Draft Subpart R (TFI) Webpage Language
Attachments: TFI draft website_8-11-20 jw.docx

Hi Stefanie - A few suggestions for your consideration. It is looking good!

Jess

Jessica Wieder
Director, Center for Radiation Information and Outreach
U.S. Environmental Protection Agency
Radiation Protection Program
w: 202-343-9201
c: 202-420-9353

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, August 11, 2020 9:10 PM
To: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: For Review | Draft Subpart R (TFI) Webpage Language

Jess,

Attached is the draft Subpart R webpage language I am proposing. This includes a small section related to the TFI application. Joe has reviewed the draft and had minimal comments. I did not hear back from Jon today.

Ex. 5 Deliberative Process (DP)

Please let me know if you have any questions, and as always, I would appreciate any comments that you have on the draft webpage.

Thanks!
Stefanie

-----Original Message-----
From: Bacon, Stefanie
Sent: Tuesday, August 11, 2020 10:20 AM
To: Wieder, Jessica <Wieder.Jessica@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: TFI--Anne has the draft letter

Jess,

Thanks for touching base. Here's where I stand with TFI. Support needed from you is noted below.

Ex. 5 Deliberative Process (DP)

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-----Original Message-----
From: Wieder, Jessica <Wieder.Jessica@epa.gov>
Sent: Tuesday, August 11, 2020 10:13 AM
To: Lee, Raymond <Lee.Raymond@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: FW: TFI--Anne has the draft letter

Can you both - drop me a note letting me know what actions you are currently taking of TFI. I just want to be able to report out accurately to Rick at my general tomorrow.

Ray - I just called to make sure you have everything you need (including someone working with you) on the TFI FR.

Stefanie - Is there anything you need from me?

Jess
Jessica Wieder
Director, Center for Radiation Information and Outreach U.S. Environmental Protection Agency Radiation Protection Program
w: 202-343-9201
c: 202-420-9353

-----Original Message-----
From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Tuesday, August 11, 2020 9:16 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Nagata, Jonathan <Nagata.Jonathan@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: FW: TFI--Anne has the draft letter

Ex. 5 Deliberative Process (DP)

Thanks!

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

-----Original Message-----
From: Peake, Tom
Sent: Monday, August 10, 2020 1:20 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: TFI

Attached is latest version of the TFI letter (August 10 file). I cleaned up the previous version (also attached) to get rid of the comments and added some language around the reclaimer scenario after talking with Charles.

Ex. 5 Deliberative Process (DP)

I am on leave this afternoon. Dan will be in.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

-----Original Message-----
From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, August 10, 2020 11:22 AM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>
Subject: TFI

Hi Jon,

Ex. 5 Deliberative Process (DP)

Sent from my iPhone

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 11/21/2019 2:57:28 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
CC: Wieder, Jessica [Wieder.Jessica@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
Subject: RE: FR notice options
Attachments: Awareness Briefing for Managment on TFI Petition 11-21-19.docx

Ex. 5 Deliberative Process (DP)

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Thursday, November 21, 2019 9:39 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: FR notice options

Here is an updated version of the document.

If you don't mind dialing me at 11, it might be helpful for me to listen to the discussion. It's not necessary, though.

- Jon

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, November 21, 2019 8:54 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: FR notice options

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Tuesday, November 19, 2019 3:12 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: FR notice options

Here's the second draft for Tom's and Dan's review.

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 10/15/2020 7:36:53 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
CC: White, Rick [White.Rick@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.--I like the write-up. Could we please add the web link and finalize?

This language looks good to me. Please forward on to the press office for distribution. Thanks to all.

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 3:33 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.--I like the write-up. Could we please add the web link and finalize?

Circulating for final approval. I have also added the docket reference to Tony's additional text.

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https://www.epa.gov/radiation/approval-other-uses-phosphogypsum-supporting-documents

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Thursday, October 15, 2020 3:26 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.--I like the write-up. Could we please add the web link and finalize?

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From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 3:21 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

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From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, October 15, 2020 3:17 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

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Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 2:58 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

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From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, October 15, 2020 2:45 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica

<Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

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From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 2:42 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

Here is some suggested language for others to massage as desired:

Ex. 5 Deliberative Process (DP)

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, October 15, 2020 2:32 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

Who can prepare a first draft for Tony?

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 2:23 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

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From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 2:11 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

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Ex. 5 Deliberative Process (DP)

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Thursday, October 15, 2020 1:55 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: Media Inquiry from Center for Biological Diversity: DDL COB today.
Importance: High

Dear Dan, Jon, and Tom:

The Center for Biological Diversity just sent this question in via the Press Office. Do you think we could provide an answer by COB today? I tried to draft an answer based on the Subpart R website text and our previously approved press answers, but it needs your input and approval. I'll be in our Center meeting starting at 2.

Question:

The last time it was evaluated for use in roads, the EPA found that the gypsum in FL was to radioactive for that use. (http://www.fipr.state.fl.us/about-us/phosphate-primer/phosphogypsum-and-the-epa-ban/). Without seeing the EPA's analysis (assuming there is one), I can't imagine what has changed, except the agency's tolerance for which and how many people get sick or die as a result of exposure.

Ex. 5 Deliberative Process (DP)

Tony Nesky
Center for Radiation Information and Outreach
Tel: 202-343-9597
nesky.tony@epa.gov

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 8/10/2020 3:06:59 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]
Subject: Reminder: Work on TFI FAQ sections for this Wednesday

Hi everyone,

I wanted to send out a reminder for everyone to work on answers for your sections on the FAQ for our next TFI meeting this Wednesday (8/12). We're going to continue discussing them during the technical TFI meeting on Wednesday. Here's the link to the document on the SharePoint (same as the attached document):

Ex. 5 Deliberative Process (DP)

Thanks,

Joe

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 10/20/2020 1:21:43 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]
CC: Peake, Tom [Peake.Tom@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: RE: Approval of Request for Other Use of Phosphogypsum

It did get cleared yesterday and went to Tony and Ray. Ray submitted it to the docket.

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, October 20, 2020 9:20 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Approval of Request for Other Use of Phosphogypsum

Tony can correct me, but as of yesterday, we were waiting to receive the technical review. Jon expected that we would receive it soon, but we can't post it until we have it (and have permission for it to go public).

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Tuesday, October 20, 2020 9:06 AM
To: Diaz, Charlene <diaz.charlene@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Approval of Request for Other Use of Phosphogypsum

It would just save them some time searching, if they don't already have them. You can provide our website link, although it doesn't look like the technical review is posted yet (Tony, is that right?). As of about 8:30, the docket wasn't showing anything other than the FR notice. But the technical review will be on the website and the docket today.

From: Diaz, Charlene <diaz.charlene@epa.gov>
Sent: Tuesday, October 20, 2020 9:01 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>
Subject: RE: Approval of Request for Other Use of Phosphogypsum

Hi Dan,

I sent the link to the Regions that you provided this morning. Would you like for me to forward these documents to then as well? I know there was a request to receive the analysis document.

Thanks,
Charlene

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator

Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Tuesday, October 20, 2020 8:46 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Subject: FW: Approval of Request for Other Use of Phosphogypsum

Here's what I sent ASTSWMO. Kerry Callahan is the ASTSWMO staff person we deal with for the Radiation Task Force, which is under the Materials Management Subcommittee. Feel free to edit as appropriate to make it CRCPD-specific.

I'd suggest having Charlene send anything to the regions. We did have a call yesterday and gave them an overview, and I think they might have the website.

From: Schultheisz, Daniel
Sent: Tuesday, October 20, 2020 8:29 AM
To: Kerry Callahan <KerryC@astswmo.org>
Subject: Approval of Request for Other Use of Phosphogypsum

Kerry:

You may have heard something about this, but I wanted to let you know that on October 14 EPA approved a request by The Fertilizer Institute (TFI) for use of phosphogypsum in government road construction projects. This approval is granted under the Clean Air Act and the provisions in 40 CFR 61.206, which allow EPA to approve other uses of phosphogypsum if they can be demonstrated to be at least as protective as keeping the material in a stack, which is the designated management method.

This approval is subject to terms and conditions, and we are not aware of any such projects under consideration at this time. A government agency proposing to use phosphogypsum in this manner would have to submit additional information to EPA and provide an opportunity for the public to review the proposal and documents related to this approval, including the risk assessment submitted by TFI. A key condition is that the road not be abandoned or converted for non-road uses, unless additional risk analyses are conducted and EPA is notified.

I thought this action would be of interest to the Materials Management Subcommittee, as states contemplating such use may have to conduct their own analyses to approve any such projects. EPA's approval is strictly limited to the Clean Air Act, and does not relieve TFI or end users of the responsibility to comply with any other applicable laws or regulations.

Attached are the approval letter and the Federal Register notice, which was published today. You can find more information at https://www.epa.gov/radiation/subpart-r-national-emission-standards-radon-emissions-phosphogypsum-stacks. The official docket for this action can be accessed through www.regulations.gov, search for Docket No. EPA-HQ-OAR-2020-0442.

Please let me know if you have any questions. Thanks.

Dan

Message

From: Peake, Tom [Peake.Tom@epa.gov]
Sent: 8/6/2020 5:07:15 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]
CC: Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: TFI draft approval letter from Charles
Attachments: Response to TFI-Draft Conditions Letter Austin to TFI August 4 CStarrs TPeake.docx

All,

Ex. 5 Deliberative Process (DP)

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Nesky, Anthony [Nesky.Tony@epa.gov]
Sent: 10/15/2020 6:28:35 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
CC: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

Ex. 5 Deliberative Process (DP)

Tony

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 2:27 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

Also, in the comms plan Qs 15-17 we address the issue, though the questions aren't set up exactly the same as this one.

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 2:23 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

Ex. 5 Deliberative Process (DP)

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 2:11 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Media Inquiry from Center for Biological Diversity: DDL COB today.

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Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Thursday, October 15, 2020 1:55 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: Media Inquiry from Center for Biological Diversity: DDL COB today.
Importance: High

Dear Dan, Jon, and Tom:

The Center for Biological Diversity just sent this question in via the Press Office. Do you think we could provide an answer by COB today? I tried to draft an answer based on the Subpart R website text and our previously approved press answers, but it needs your input and approval. I'll be in our Center meeting starting at 2.

Question:

The last time it was evaluated for use in roads, the EPA found that the gypsum in FL was to radioactive for that use. (http://www.fipr.state.fl.us/about-us/phosphate-primer/phosphogypsum-and-the-epa-ban/). Without seeing the EPA's analysis (assuming there is one), I can't imagine what has changed, except the agency's tolerance for which and how many people get sick or die as a result of exposure.

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Ex. 5 Deliberative Process (DP)

Tony Nesky
Center for Radiation Information and Outreach
Tel: 202-343-9597
nesky.tony@epa.gov

Message

From: Wieder, Jessica [Wieder.Jessica@epa.gov]
Sent: 4/8/2020 1:29:56 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: Fw: Revised Petition, Response to Questions, etc.
Attachments: 4-7-2020 PG Petition.pdf; Appendix 3 - Metals Risk Screening.pdf; Appendix 4a - Response to Jan 16 2020 Questions.pdf; Appendix 4b - Response to Second Set of EPA Questions.pdf; Appendix 5 - Sampling Report.pdf; Appendix 6 - Economic Report.pdf; Appendix 7 - Location of PG Stacks.pdf; Appendix 8 - Administrative Record.pdf; Attachment A - Road Specs.pdf

FYI -

Jessica Wieder
Director, Center for Radiation Information and Outreach
U.S. Environmental Protection Agency
Radiation Protection Program
w: 202-343-9201
c: 202-420-9353

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Wednesday, April 8, 2020 9:07 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Boyd, Mike <Boyd.Mike@epa.gov>; DeCair, Sara <DeCair.Sara@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Cc: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: FW: Revised Petition, Response to Questions, etc.

Hi all,

The TFI info came in.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Andy O'Hare <aohare@tfi.org>
Sent: Wednesday, April 08, 2020 8:25 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: Revised Petition, Response to Questions, etc.

Lee and Jon,

Good morning. I hope this finds you both well.

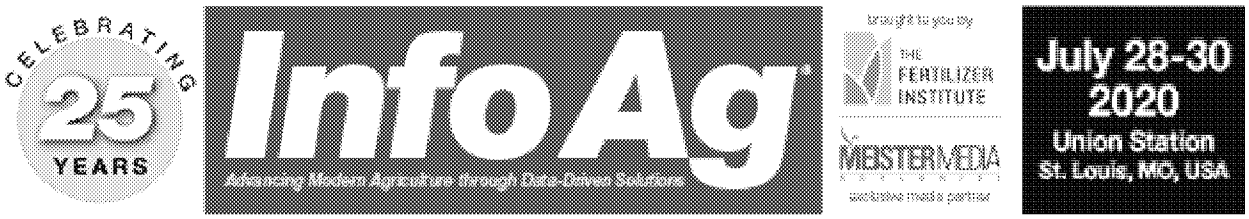
Attached is a updated version of the PG petition, response to the EPA questions on the risk assessment posed in January, response to the questions on the reclaimer scenario, and other assorted supporting appendices, some of which you have already seen. Not attached are Appendices 1 and 2, which accompanied the submittal in October 2018. I would be happy to resend these to your attention, if so desired.

Please confirm that you received these files (9 in all).

I will reach out early next week to discuss next steps in the petition review process and the potential need for a conference call.

Regards,
Andy

Andrew (Andy) T. O'Hare, CAE
Vice President, Public Policy
The Fertilizer Institute
425 Third Street, SW
Suite 950
Washington, DC 20024
(202) 515-2704 (office)
(202) 270-0094 (cell)
aohare@tfi.org



April 7, 2020

IN THE UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

REVISED REQUEST FOR APPROVAL OF ADDITIONAL USES OF PHOSPHOGYPSUM PURSUANT TO 40 C.F.R. § 61.206

Use in Road Construction projects authorized by federal, state and local Departments of Transportation or Public Works

Submitted by: **The Fertilizer Institute on Behalf of Its Members**

Andrew (Andy) T. O'Hare, CAE
Vice President, Public Policy
The Fertilizer Institute
425 Third Street, SW, Suite 950
Washington, DC 20024
(202) 515-2704 (office)

CONTENTS

This Petition and supporting risk analysis were developed by reviewing the "Applying to EPA for Approval of Other Uses of Phosphogypsum: Preparing and Submitting a Complete Petition under 40 CFR 61.206, A Workbook" (EPA PG Workbook) and prior petitions, and through a series of working meetings with EPA staff to obtain EPA input and direction on key elements of the analysis. Throughout this process, the methodologies and technical issues utilized in the technical evaluations were informed by EPA's feedback.

This Petition includes the following sections:

Section	Description
Preamble	Key Definitions
I	Overview
II	Petition Request and Legal Review Process
III	Regulatory History and Recent Developments
IV	Summary of Supporting Scientific Information
V	Application of Risk Management Factors to use of PG in road construction
Attachment A	Reference Road Construction Specifications

This Petition is supported by the following information:

Appendix	Description
Appendix 1	Summary of the Risk Assessment and Metals Screening Report (same as October 2019 Petition submission)
Appendix 2	Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum (same as October 2019 Petition submission)
Appendix 3	Human Health Risk Screening for Metals and Metalloids
Appendix 4	4a: Response to EPA Comments on January 16, 2020 and 4b: Responses to Second Set of USEPA Questions on March 6, 2020 – Reclaimer
Appendix 5	Report on recent measurements of PG radioactivity level in U.S. stacks
Appendix 6	Policy Navigation Group, Economic Analysis of Phosphogypsum Reuse (December 2019)
Appendix 7	Location of PG stacks (mailing address for the Petitioners is the TFI address on the Petition cover and the addresses in Appendix 7)

Appendix 8	Other documents being submitted for the administrative record

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DEFINITION OF KEY TERMS

The basic concepts relevant to this Petition are:

Dose: Dose measures the amount of radiation absorbed by a person. The terms radiation absorbed dose (rad) and gray (Gy) describe measurements of the absorbed dose.

1 gray (Gy) is equivalent to 100 rad; 1 rad = 0.01 Gy

Dose equivalent adjusts the absorbed dose to include the relative medical effects of gamma rays, alpha or beta particles, x-rays, or neutrons, e.g., the effects of alpha and neutron radiation are more damaging to the human body than gamma radiation.

The dose equivalent is measured in rems (roentgen equivalent man) or 1/1000th of a rem (millirem or mrem). A rem for each type of radiation is equal to the absorbed dose (in rads) times a quality factor that reflects the fact that some types of radiation cause more damage than others [see "Units of Radiation Dose," 10 CFR § 20.1004]. The scientific community is shifting to use the nomenclature developed for the international system unit, so the term sievert (Sv) is often used.

1 rem = 0.01 sievert (Sv); 1 sievert (Sv) = 100 rem; 1 millisievert (mSv) = 0.1 rem or 100 mrem.
100 rem is equivalent to 1 Sv or 0.1 rem (or 100 mrem) equals 1 mSv.

Effective Dose is the tissue (organs) weighted sum of equivalent doses summed over all specified tissues and organs where each tissue is assigned its own tissue weighting factor (written as w_T). The tissue weighting factor is intended to represent the relative contribution of that tissue or organ to the total health detriment resulting from unform irradiation of the whole body.

Government Road Project for purposes of this Petition, means a road construction or repair project that is authorized by federal, state or local governments consistent with applicable Federal Highway or state Departments of Transportation (DOT) standards and specifications, including public works departments that have adopted the state DOT standards and specifications or developed such standards in consultation with state regulatory authorities (such as the Federal Highway Administration (FHWA) regulations and guidance, State Department of Transportation (DOT), American Association of State Highway (AASHTO), American Society for Testing and Materials (ASTM)) or other generally accepted specifications for road building.

Petition Maximum average radium (226) concentration limit: The Petition requests that EPA approve use of PG containing an average radium (226) concentration up to 35 pCi/g in road construction. The 3 in 10,000 risk level (EPA's safe level) corresponds to an average radium (226) concentration of 148 pCi/g. Thus, this proposed limit is presumptively safe.

The requested limit of 35 pCi/g is consistent with the 2019 stack sampling and with prior sampling conducted by EPA. Specifically, the broad sampling data demonstrates that PG taken from the stacks is not expected to exceed that limit. As background, the risk assessment used 27 pCi/g for its baseline evaluation (this correlates to the international standard of 1Bq) and extrapolated to reach conclusions for 35 Ci/g (see Nominal radium 226 concentration definition below). An average radium (226) concentration of 35 pCi/g for PG used in road construction materials accounts for potential variability (~30 percent) observed in past testing and during implementation of road construction.

Nominal radium (226) concentration: The radium (226) concentration level utilized in the underlying Risk Assessment filed with the petition (the Petition's Risk Assessment) is a nominal radium (226) concentration of 27 pCi /g. This particular nominal concentration was chosen so that the submission contained a calculated risk using RME, which corresponds to a "nominal" concentration of radium (226). Since the relationship of radium (226) concentration in PG to risk is proportional, the risk from using PG containing any other concentration of radium (226) in road construction can be calculated from the nominal concentration.

Radioactivity is a measure of the amount of gamma rays, alpha or beta particles, x-rays, or neutrons that disintegrate from a gram of the substance being measured (in our situation, in each gram of PG). The amount of radioactivity in a gram of a substance is measured in curies (Ci) or becquerels (Bq). One curie is 3.7×10^{10}

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radioactive decays per second, roughly the amount of decays that occur in 1 gram of radium per second. A Becquerel is one disintegration per second. Historically, scientists originally used units of Ci. The International System of Units (ISU) now uses Bq.

A picocurie (pCi) is one-trillionth of a curie.
1 Bq = 2.70 x 10^{-11} curies = 0.027 pCi

Many substances (often naturally occurring substances) are radioactive. Generally, the sources for this explanation include EPA, *Radiation Terms and Units*, *available at* https://www.epa.gov/radiation/radiation-terms-and-units; NRC, *available at* https://www.nrc.gov; MIT News, *Explained: rad, rem, sieverts, becquerels A guide to terminology about radiation exposure*, *available at* http://news.mit.edu/2011/explained-radioactivity-0328; National Aeronautics and Space Administration, *Radiation Math*, *available at* https://www.nasa.gov.

Radium (226) concentration level that corresponds to 3 in 10,000 risk management level that EPA has designated as safe. The risk assessment performed for the Petition demonstrates that PG containing a radium (226) concentration of 148 pCi/g presents a risk of 3 in 10,000 (EPA's safe level).

Reasonable Maximum Exposure: An estimate of a conservative exposure case, well above the average case, that is still within the range of possible exposures.

Risk: The regulatory risk assessment process converts a dose equivalent (in mrem) into an upper bound risk (or probability) of developing fatal cancers. It is based on a regulatory assumption that the dose equivalent may cause harmful effects and as the magnitude of this dose increases or decreases, the risk increases or decreases, in direct proportion, respectively, i.e., linearly (e.g., if the dose is halved, the calculated risk is halved). The risk assessment performed for this Petition concludes that an effective dose of 600 millirem corresponds to a risk of 3 in 10,000 (i.e., if all of the protective assumptions are valid, 3 in 10,000 people may develop a fatal cancer). The actual risk is likely to be lower.

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I. OVERVIEW

A. INTRODUCTION

Approximately 46 million tons of phosphogypsum (PG) is produced annually in the U.S. as a byproduct of the phosphate fertilizer production process.[1] For decades, the majority of PG has been placed in large engineered gypstacks, instead of using the material in various applications.

Internationally, PG is used in road construction, concrete and building material production, agriculture, mine restoration, marine applications and for daily landfill cover. Scientific studies completed in both the U.S. and internationally support these beneficial uses of PG. The studies demonstrate use of PG in numerous applications is protective of human health and the environment and, at least as protective of human health as storage of PG in a stack.

This Petition, submitted by The Fertilizer Institute[2] (TFI), requests approval for PG use in government road construction projects. The request is submitted pursuant to the United States Environmental Protection Agency's (EPA) rule governing the distribution and use of phosphogypsum for purposes other than disposal in a stack. See 40 CFR §61.206.[3] Under this provision, a request for a proposed use with supporting information[4] must be submitted to EPA. The request is followed by EPA review and a determination allowing or rejecting the proposed use. EPA may make a determination granting the request if the proposed use is at least as protective of public health, in the short and long term, as disposal in a stack. If EPA makes a determination approving the proposed use, specific information in connection with the projects conducted must be certified and maintained for five years. For example, each time PG is removed from the stack for the approved use, the stack owner/operator must certify the identity and location of the user, the quantity of PG provided, a description of the end use, and the average radium 226 concentration.

This Petition should be approved by EPA because:

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[1] Policy Navigation Group, Economic Analysis of Phosphogypsum Reuse, 12 (December 2019) (Prepared for TFI), based on weighted average PG production per stack.

[2] TFI is the leading voice of the fertilizer industry, acting as an advocate for fair regulation and legislation, a consistent source for trusted information and data, a networking agent, and an outlet to publicize industry initiatives in safety and environmental stewardship. The fertilizer industry contributes $155 billion to the nation's economy. TFI, available at https://www.tfi.org/policy-center/economic-impact. The fertilizer producers, wholesalers and retailers, along with the businesses that serve them, support nearly half a million U.S. jobs with total annual compensation of $36 billion. *Id.*

[3] EPA, National Emission Standards for Hazardous Air Pollutants; Radionuclides, 54 Fed. Reg. 51,654 (December 15, 1989) (1989 Rule).

[4] The supporting information includes: petitioner identity, description of the proposed use, street location and mailing address of the facility where use, handling or processing of PG occurs, quantity of PG to be used, average radium (226) concentration in PG that will be used, measures to prevent PG releases to the environment, risk associated with the proposed use, including ultimate disposition, management of unused PG, requestor signature.

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- The risk of radiation exposure from use of PG in road construction is low, well within EPA's 3 in 10,000 lifetime cancer risk determined to be safe and well below natural background exposure levels.

- Demand for available, cost-effective road construction materials is high. This is particularly true where other materials widely used in road construction, such as coal ash, are anticipated to become scarce and more expensive due to new regulatory contraints on production and storage.[5] Radiation from PG is similar or less than other materials currently used in road construction.

- Use of PG in road construction has environmental and societal benefits, reducing the amount of material required to be stored in stacks (and potentially eliminating existing stacks over the longer term).

- There are other economic and societal benefits (discussed in more detail in Appendix 6).

B. BACKGROUND

PG is a byproduct of the phosphate fertilizer production process. At a typical U.S. facility, approximately five tons of PG are generated per ton of phosphoric acid produced. Prior to 1989, PG was used in various applications (including, among other uses, in the construction of roads and in agriculture).

NESHAP Regulations Governing PG. Thirty years ago, EPA restricted the use of PG based on the estimated risk from exposure to naturally occurring radioactive material (NORM) in the material. These restrictions are set forth in the regulations governing the management of PG in EPA's National Emission Standards for Hazardous Air Pollutants (NESHAP), Subpart R of title 40 of the Code of Federal Regulations. Subpart R requires that, with very limited exceptions for agricultural use and indoor research, PG must be placed in engineered above ground impoundments (commonly referred to as "gypstacks").[6]

With respect to the stacking exceptions, Section 61.206(a) allows removal of PG from stacks without prior approval[7] for: (i) outdoor agricultural use of PG containing an average radium-226 concentration not exceeding 10 picocuries per gram (pCi/g) (§61.204) and (ii) indoor research and development not to exceed 7,000 pounds (§61.205).[8] These uses are self-implementing; no

---

[5] Texas Department of Transportation, Technical Advisory, Fly Ash Supply Update (updated 2019), *available at* http://ftp.dot.state.tx.us/pub/txdot/mtd/ta/fly_ash_condensed.pdf. Danny L. Gray, Decrease in Fly Ash Spurring Innovation Within Construction Materials Industry, Vol. 35, Issue 6, Special Issue: Annual Outlook Issue (Jan. 2019), *available at* https://onlinelibrary.wiley.com/doi/pdf/10.1002/gas.22099.

[6] 40 CFR §§ 61.200 - 201.

[7] EPA later approved placement of PG as landfill cover in a test cell to determine if PG can be used more broadly as a landfill cover. Letter from Jeffrey R. Holmstead, Assistant Administrator of the Office of Air and Radiation, to Michael Lloyd, Jr., Research Director Chemical Processing, Re: FIPR Petition (December 22, 2004) (Holmstead FIPR Letter).

[8] 40 CFR §§ 61.204 - 61.205.

additional authorization is required. However, the stack owner and the user must comply with specific reporting and record keeping requirements.[9]

Any other uses must first be approved by the EPA Assistant Administrator for Air and Radiation. Under Section 61.206(c), the request may be approved if the proposed use is determined to be at least as protective of public health, in both the short term and the long term, as disposal of PG in a stack.

Post-NESHAP Developments. Since the NESHAP was promulgated decades ago there have been a number of developments in various realms that support broader use of PG.

- **New Scientific Information**. New data are available on the average level of radioactivity in the PG. There is also a better understanding in the scientific community concerning radiation protection and management related to PG use. Studies have been completed in the U.S. and internationally supporting expanded beneficial use of residual material from manufacture of fertilizer; these studies demonstrate protectiveness of human health and the environment.

- **Risk Assessment and Policy Updates**. Risk assessment approaches have progressed based on experience, analytical advances, and evolving policies since the 1980s.

  For example, EPA's prior assessments of the risk from use of PG in road construction (e.g., in the 1989 regulations and the EPA 1992 Background Information Document) did not evaluate the potential radiation risk from every possible road design. Rather, EPA recognized that it is not necessary to calculate every potential exposure. It is appropriate and consistent with EPA policy to examine risk by utilizing a "reasonable maximum exposure" approach (RME). According to EPA, the RME is "a conservative exposure case, (i.e., well above the average case) that is still within the range of possible exposures."[10] EPA guidance states that the assessor may derive a high-end estimate of exposure by using maximum or near maximum values for one or more sensitive exposure

[9] 40 CFR §§ 61.206 – 209. Approvals under §61.206(b) require compliance with sampling procedures (§61.207), certification requirements (§61.208), and records rquirements (§61.209(c)), unless the Assistant Administrator decides to waive or modify the record keeping requirements.

[10] EPA, Risk Assessment Guidance for Superfund: Volume III - Part A, Process for Conducting Probabilistic Risk Assessment, EPA 540-R-02-002, 7-1 (2001), *available at* https://www.epa.gov/sites/production/files/2015-09/documents/rags3adt_complete.pdf. (EPA Risk Assessment Guidance for Superfund).

See also Interstate Technology Regulatory Council (ITRC), Decision Making at Contaminated Sites, Issues and Options in Human Health Risk Assessment, 6.1.1 (2015), *available at* https://www.itrcweb.org/risk-3/Default.htm#6.%20Exposure%20Assessment.htm#6.1__Determining_Appropriate_Exposure_Factors%3FTocPath%3D6.%2520Exposure%2520Assessment%7C6.1%2520%2520Determining%2520Appropriate%2520Exposure%2520Factors%2520%7C_____0 (ITRC, Decision Making at Contaminated Sites) (citing EPA Guidance, which states that "[t]he RME . . . can be defined as 'the maximum exposure that is reasonably expected to occur within a potentially exposed population'").

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factors, leaving others at their mean value.[11] Therefore, RME is not the worst-case exposure and a worst-case exposure analysis was not required by EPA.

RME provides the exposure used to calculate the maximum individual risk (MIR). As long as the risk from RME does not exceed 3 in 10,000, the exposure is "safe" (see discussion of EPA's policy on the safe risk level for PG (Section IV, below)). By definition, if the risk from a RME exposure for construction workers, truck drivers, road users, and residents is below 3 in 10,000 and, therefore, safe, all other exposures to workers, truck drivers, road users, and residents present even less risk (and in many cases, the risk is much less than 3 in 10,000).

Additionally, there has been an increased awareness of product lifecycles and sustainability. Accordingly, current EPA policies encourage use and recovery of high-volume, low-risk waste. This includes increased emphasis on understanding product lifecycles and sustainability.

- **Regulatory.** It has become apparent that the current requirement to obtain regulatory approval for each and every application of a new use is unwieldy and slows the process of implementing new uses without providing additional protection of human health (i.e., use of updated scientific and risk assessment assumptions demonstrate that road use is safe). As a result, the past interpretations impede innovation and economic efficiencies. The fact that no PG use requests have been submitted in almost 30 years (except for a landfill cover test cell) illustrates this point.

- **Commercial Economics and International Use Precedents.** The economics of gypstacks have changed. The cost to stack and manage gypstacks has increased substantially beyond original expectations. These costs adversely affect the ability of the U.S. fertilizer industry to compete internationally, where PG may be used.

  PG is used in many countries outside the U.S. in agriculture, mine restoration, building materials, marine applications, daily landfill cover, and for road construction. More than a dozen beneficial uses have been analyzed worldwide, resulting in significant, successful PG use applications in at least 21 countries.[12]

- **Public Perception.** Perceptions of gypstacks have changed. EPA's 1989 final rule did not anticipate the range of public sentiment regarding the long term presence of gypstacks. Public pressure to cease this practice is growing.

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[11] EPA, Exposure Factors Handbook 2011 Edition (Final Report), EPA/600/R-09/052F (2011), *available at* https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252 (Exposure Factors Handbook).

[12] *See* Presetnation by The Fertilizer Institute, Beneficial Use of Phosphosgypsum (Sept.6, 2018). *Also see* B. Birky, J. Hilton, & AE J. Johnston, Phosphogypsum: Sustainable Management and Use, International Fertilizer Association, Chp 5, 52-63 (2016), *available at* https://www.fertilizer.org/ItemDetail?iProductCode=10012Hardcopy&Category=ENV (IFA Sustainable PG Management Report). This section reviews international and U.S. roads constructed with PG. Other chapters address other uses.

Beneficial Use of PG in Government Road Projects. Based on the developments and framework described above, TFI submits this Petition seeking approval of PG for use in government road projects.[13] The scope of this request is described below.

- **Description.** A paved road consists of a solid surface or top layer that is typically asphalt, concrete, or some other material or mixture approved for use as pavement. The road base is a supporting layer of material approximately 0.25 m thick beneath the surface/pavement and underlying the road base is the sub-grade (as shown in Figure 1). The proposal is for approval of use of PG as road base or surface pavement.

- **Design.** PG may be used as road base or surface pavement when mixed with other materials such as soil, sand or aggregate or in the surface pavement. This Petition requests approval for use of up to (i) 2.5% PG in surface pavement and (ii) 50% PG in road base. This mixture is based on a design of up to equal amounts of PG and soil in roadbed.[14] Using a ratio of 50% or less PG mix in road base, approximately 4000 tons of PG per lane-mile would be used in road base and less than 100 tons per lane-mile would be used in concrete pavement (Appendix 4a: Response to EPA Comments on January 16, 2020).

  These ratios are supported by prior technical evaluations. For example, various ratios of PG to soil were studied (from 100% sand to 100% PG) and all mixes had California Bearing Ratio values higher than sand or PG separately. Studies of the road containing PG in Polk County Florida found similar results (Appendix 4a: Response to EPA Comments on January 16, 2020).

- **Exposure analysis.** The road design features analyzed in the Petition (Appendix 2),[15] the Metals Screening Report (Appendix 3), and Response to EPA Comments on January 16, 2020 (Appendix 4a)) were determined to represent RME for all road designs, regardless of the size of the road. That is, the radioactivity levels emitted from the road in using these design assumptions were RME assumptions and did not exceed 3 in 10,000 (Appendix 4a). Thus, assuming the RME calculation is appropriate, the radioactivity exposure risk associated with all other road designs is less than 3 in 10,000, the EPA determined acceptable risk level.

  EPA's 1992 BID risk assessment approved the use of PG for agricultural soil amendments as safe.[16] The EPA 1992 BID risk assessment assumed biennial applications of PG over 100 years on agricultural soil (with the PG containing a radium

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[13] The Petition for PG use in road construction covers only paved roads that meet the definition of "Government Road Project" included in this Petition. Unpaved roads have not been evaluated and are not within the request.

[14] This is an upper bound because industry practice recommends similar ratios or less and EPA's 1992 risk assessment used 33.3 percent PG to 66.6 percent soil (see Appendix 2).

[15] EPA, Potential Uses of Phosphogypsum and Associated Risks, Background Information Document, 402 R92 002, 4 26 4 35 (May 1992), *available at* https://www.epa.gov/sites/production/files/2015-07/documents/0000055v.pdf (EPA 1992 BID).

[16] *Id.* at 4-26.

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(226) concentration of 10 pCi/g) and no cover.[17] EPA assumed that approximately 2,700 pounds of PG per acre is "spread over a field and diluted by mixing with the soil." [18]

Unlike PG in agricultural use, PG used in road base is mixed with soil (50% PG and 50% soil), application is one-time and not repeated, and there is no cumulative concentration of radium (226).

In each case, the risk is based on the exposure assumptions utilized. The radiation dose (and, therefore the risk) is a function of the average radium (226) in the road base (or cement), not the volume of PG used in a road application.

Figure 1 provides a conceptual view; municipal roads can vary in width and structure.

- **PG Users.** This Petition requests approval to use PG in ***government*** road construction projects. Thus, the authorized users of the PG would include federal, state and local Departments of Transportation (DOT) or Public Works (PW), and their contractors. Only these governmental agencies are authorized to commission governmental roadways.

- **Project Locations.** Given transportation costs, government PG road construction projects are expected to be located in states that are in sufficient proximity to the PG stacks (i.e., Florida, Georgia, North Carolina, Idaho, Louisiana) to make PG use economically viable. Appendix 7 provides the location of the PG stacks associated with TFI member operations.

- **Project Specifications.** TFI reviewed how similar materials used in road construction are managed to determine how PG would be handled, transported, stored and used in federal, state or local government road projects. PG would not be the first byproduct to be used in road construction (see below). Nor would it be the first byproduct for which road construction specifications were developed to substitute the use of a byproduct for other road building material. Government (particularly State) DOTs have considerable experience in this regard.

While there are distinctions between PG and coal ash, the regulation of coal ash by the states is analogous because the materials are excluded from federal regulation under the RCRA Bevill amendment (42 U.S.C. § 6921(b)(3)(A), Resource Recovery and Conservation Act § 3001(b)(3)(A)). Currently, according to EPA:

> [S]tate environmental agencies are primarily responsible for regulating beneficial use [of coal ash, because the] use of coal combustion residuals is currently excluded from federal regulation under EPA's May 2000 regulatory determination that the Bevill amendment applies to such uses. [and] [t]he April 2015 final … [coal combustion] disposal rule reaffirm[ed] EPA's Bevill determination.[19]

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[17] *Id.*at 4-5 - 4-6.

[18] *Id.* at 4-5.

[19] EPA, Coal Ash Reuse, How is the Beneficial Use of Coal Ash Currently Regulated? (last updated July 15, 2019), *available at* https://www.epa.gov/coalash/coal-ash-reuse. Tecnically, the Bevill amendment applies to the type of

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Analogously, the use of PG is regulated by the Clean Air Act NESHAP regulatory program based on the radioactivity in PG, but otherwise is excluded from federal regulation under the RCRA Bevill amendment.

Government road projects are constructed in accordance with overarching Federal Highway Administration (FHWA) regulations and guidance, under the direct supervision of state Department of Transportation (DOT) requirements. "Because roadway location and design decisions affect the development of adjacent areas, it is important that environmental variables be given full consideration."[20] These specifications dictate how various materials may be used, based on strength and stiffness considerations, permeability, and stability, among other factors. [21] The FHWA released guidelines for use of coal fly ash and other materials (e.g., kiln dusts) in asphalt concrete, Portland cement concrete, stabilized base, flowable fill, and embankment or fill.[22]

Specifications are designed using various materials testing methods developed by these professional organizations, such as AASHTO and ASTM. Thus, since the RME were selected based on the road construction project meeting these design criteria, the risk assessment represents RME.

State Regulatory Programs. In addition to EPA's NESHAP determination, use of PG in road construction will be subject to state regulation and oversight. State regulatory programs developed for managing use of industrial by-products will apply as will state specifications for road construction.

For example, the Florida Department of Transportation's Standard Specifications For Road and Bridge Construction state that roads must: (a) "[p]rovide erosion control measures where work is accomplished in conjunction with the project, to prevent erosion, pollution of water, detrimental effects to public or private property adjacent to the project right-of-way and damage to work on the project;" (b) "not drive in, operate, or place construction equipment or materials in surface waters, wetlands, groundwater, or property beyond the project limits without permitted

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waste, not just to the use. The quote describes EPA's application of the Bevill amendment in this particular use. From a broader perspective, it highlights the fact that state regulators have jurisdiction over many types of waste.

[20] Association of State Highway and Transportation Officials (AASHTO), A Policy on Geometric Design of Highways and Streets, 7th Ed., 2-95 (2018), *available at* https://store.transportation.org/item/collectiondetail/180?AspxAutoDetectCookieSupport=1 (The Green Book) (an online guidance that is over 1,000 pages). AASHTO is a nonprofit, nonpartisan association representing highway and transportation departments and a leader in setting technical standards for design, construction of highways and bridges, materials, and many other technical areas. Consideration of impacts on the environment are explicitly required to be considered. *Id.* at 1-2.

[21] *See* Federal Highway Administration, Tech Brief, Bases and Subbases for Concrete Pavements (revised), FHWA-HIF-16-005 (August 2017), *available at* https://www.fhwa.dot.gov/pavement/concrete/pubs/hif16005.pdf.

[22] Federal Highway Administration, User Guidelines for Waste and Byproduct Materials in Pavement Construction, Coal Fly Ash, FHWA-RD-97-148, *available at* https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/97148/016.cfm.

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authority for permanent or temporary impacts;" and (c) "not allow water that does not meet state water quality standards or does not meet the permitted criteria to exit the project limits."[23]

There are specifications for and policies encouraging the use of fly ash, slag, and/or other recycled material in roadways in Florida, North Carolina, Louisiana, and Idaho, among other states.[24] In Florida, industrial by-products are defined as:

> Materials that have a demonstrated recycling potential, can be feasibly recycled, and have been diverted or removed from the solid waste stream for sale, use, or reuse. The term does not include any materials that are defined as recovered materials, a mixed waste stream that is processed to removed recyclable materials; or materials the recycling or use of which is specifically addressed in [FDEP] rules, such as construction and demolition debris, ash residue, waste tires, used oil, and compost. Fla. Admin. Code 62-701.200(51).

Industrial by-products are regulated as solid waste unless otherwise exempted under Fla. Admin Code 62-701.200(51).

Florida is required to:

> Encourage recycling and resource recovery as a source of energy and materials. Fla. Stat. §403.704(6);

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[23] Florida Department of Transportation, Standard Specifications For Road and Bridge Construction, 131 (July 2020), *available at* https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/programmanagement/implemented/specbooks/jul2020/7-20ebook.pdf?sfvrsn=c1f3424e_4 (Florida Spec Book).

[24] See for example: Florida, Department of Transportation, State Materials Office, Frequently Asked Questions, *available at* https://www.fdot.gov/materials/administration/resources/library/issues-trends/recycling-faqs.shtm.

North Carolina Department Of Transportation Raleigh, Standard Specifications For Roads and Structures, 10-1 (slag), 1-43 (recycled) (2018), *available at* https://connect.ncdot.gov/resources/Specifications/StandSpecLibrary/2018%20Standard%20Specifications%20for%20Roads%20and%20Structures.pdf (North Carolina Spec Book).

Louisiana Department of Transportation & Development, Louisiana Standard Specifications For Roads And Bridges, 152, 200, 392, 965 (2016), *available at* http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Standard_Specifications/Standard%20Specifications/2016%20Standard%20Specifications%20for%20Roads%20and%20Bridges%20Manual/00%20-%202016%20-%20Standard%20Specification%20(complete%20manual).pdf.

Idaho Transportation Department, 2018 Standard Specifications for Highway Construction (2018), *available at* https://apps.itd.idaho.gov/apps/manuals/SpecBook/SpecBook18.pdf.

This wide spread development by the states of specifications for the use of various recycled material is strongly encouraged by the federal government. Federal Highway Administration, Recycled Roadways, FHWA-HRT-05-003 (Jan/Feb 2005), *available at* https://www.fhwa.dot.gov/publications/publicroads/05jan/02.cfm.

Similarly, see AASHTO, Center for Environmental Excellence, The Growing Need for and Importance of Waste Minimization and Recycling, subchp. 3.12.1, (last updated 2005), *available at* https://environment.transportation.org/environmental_issues/construct_maint_prac/compendium/manual/3_12.aspx.

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> Provide technical assistance to counties, municipalities, and other persons, and cooperate with appropriate federal agencies or private organizations in carrying out this Act. Fla. Stat. §403.704(2); and
>
> Assist in and encourage, as much as possible, the development within the state of industries and commercial enterprises which are based on resource recovery, recycling, and reuse of solid waste. Fla. Stat. §403.704(7).[25]

Further, the Florida DOT is required to encourage the use of products and materials with recycled content in its road construction programs and to continually update its bid procedures and specifications to encourage the use of such products and materials, *see* Fla. Stat. §336.044(4). Therefore, once EPA authorizes use of PG in road construction, the Florida DOT will have a clear path under Florida law to consider whether its existing road specifications are adequate or if any modifications are warranted.

Similarly, North Carolina has design specification guidance.[26] Notably, North Carolina includes a policy "to aid in reduction of materials that become a part of our solid waste stream."[27]

In Idaho, using fly ash as an example, materials may be used only if provided by manufacturers approved by the state's Quality Assurance Program (QAP). Manufacturers not approved under the certification program require pre-approval before use.[28] The QAP mandates sampling be conducted by accredited labs, among other requirements. Idaho has recently passed a law that requires the development of a regulatory program for PG use.[29]

Louisiana's Solid Waste Management and Resource Recovery Law directs maximum practicable use of resource recovery procedures. [30] The Louisiana Solid Waste Regulations include Section 1105: Beneficial Use of Other Solid Wastes which allows owners of waste streams to request that the waste be designated for an approved beneficial use. The application process specifies much of the same information required under the NESHAP regulation 40 CFR 61.206(b), and indicates that, at least in Louisiana, prior to any use of PG in road construction, the state may be required to make a determination similar to EPA, including approval of a handling and storage plan. [31]

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[25] Fla. Stat. § 403.704.

[26] North Carolina Spec Book, *supra* note 24.

[27] *Id.* at 1-43, Section 104-13.

[28] Idaho Transportation Department, Quality Assurance Manual, §230.02.02 (2019), *available at* https://apps.itd.idaho.gov/Apps/manuals/ManualsOnline.html.

[29] H.B. 367, 65th Leg., 2d Reg. Sess. (Idaho 2020) (signed by Gov. on Mar. 9, 2020, Sess. Law Chp. 51, eff. Jul. 1, 2020).

[30] Louisiana Solid Waste Management and Resource Recovery Law, La. Rev. Stat. § 30:2154(1).

[31] La. Admin. Code 33:VII:1:1105.

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The existence of these stringent state regulatory programs coupled with the need for a specific DOT specification for PG use in roadbuilding provide additional assurances that EPA's approval of PG use in road construction will ensure responsible handling and management of PG in road construction. Therefore, once EPA authorizes use of PG in road construction, the states will be able to make informed choices as to the most appropriate and cost-effective road construction material, while still ensuring the protection of the environment.

Public Health and Environmental Evaluation. The Petition is accompanied by a Radiological Risk Assessment (Appendix 2) and a Human Health Risk Screening for Metals and Metalloids (Appendix 3). The scope and approach to these analyses were developed based on the EPA PG Workbook, prior petitions, and a series of working meetings with EPA staff that provided the benefit of EPA input and direction on key elements of the analysis.

To assist in this evaluation, TFI members measured the radioactivity level in the PG from stacks.[32] Results reflect that average radiation levels from the composite samples taken from stacks do not exceed: (a) the nominal radium (226) concentration used in the risk analysis (i.e., 27 pCi/g) and (b) more importantly, the 148 pCi/g radium (226) concentration corresponds to the 3 in 10,000 risk management level that EPA has designated as safe (see Sections II(B), III(G), V, V(D)(3,4), below).

Key points of the Radiological Risk Assessment are provided in Attachment B. In summary, this assessment demonstrates that PG can be used safely for road construction for the following reasons:

Use of Reasonable Maximum Exposures (RME) Ensures Risk is Less than 3 in 10,000

All RMEs resulting from use of PG in road construction correspond to a risk of less than the 3 in 10,000 lifetime cancer risk (the risk level that EPA has determined to be safe for alternative PG uses and well below natural background exposure (see Summary Table 1, below, and the Petition's Risk Assessment summarizing the risks from each of the five exposure scenarios calculated for this Petition)). EPA staff clarified interest in more risk distribution information on how the risk varied with the "variation of the geometry of exposure" and with different exposure time frames (Appendix 4a: Response to EPA comments on January 16, 2020). The risk distribution is similar in each scenario with the the highest risk associated with the RME exposure scenario. Most actual exposures are less than those received by the RME and hence the associated risk would also be lower (Appendix 4a: Response to the EPA Question on January 16, 2020). For example, the risk is lower for workers who are not exposed for the same duration or as directly as the RME scenarios. The analysis also shows that the risks for the residential RME scenario are much lower than for the construction worker, truck driver, and road user. In each case, most of the exposed population have a dose that is lower than the RME dose (see Appendix 4a: Response to EPA Comments on January 16, 2020).

[32] A summary of this data was provided to EPA to support this Petition in a separate report, along with the location and address of each facility (Appendix 5).

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Table 1: Dose, Risk, and Background Summary for All RME Scenarios

Receptor	CSM	Exposure Duration (years)	Exposure Dose (mrem)	Estimated Cancer Risk	Background Dose from Exposure Duration (mrem)	Exposure Dose Percentage of Background Dose (%)
Reasonable Maximum Exposure Scenarios						
Road Construction Worker	PG in Road Base	5	110	0.5 in 10,000	1550	7%
Road User (Motorist/Bicyclist)	PG in Road Base & Surface	26	28	0.1 in 10,000	8060	0.3%
Truck Driver	PG-containing material for Road Base	5	93	0.5 in 10,000	1550	6%
Nearby Resident	PG in Road Base & Surface	26	16	0.08 in 10,000	8060	0.2%
Utility Worker	PG in Road Base	1	0.8	0.004 in 10,000	310	0.3%
	EPA Cancer Risk Management Goal		600	3 in 10,000	600	

Estimated cancer risk below this goal.

- The highest risk in the Petition's Risk Assessment was for the RME construction worker scenario --- 0.5 in 10,000 and the RME worker dose is 7% of the background dose for a worker at a road construction site not using PG (see Table 1, above, summarizing the risks from all exposure scenarios).

- The Response to the EPA Comments on January 16, 2020 expanded on the Risk Assessment by evaluating the uncertainty in each of these exposure scenarios and finding no significant increase even using the assumptions postulated in the EPA comments. In any case, the postulated assumptions were in excess of the RME and did not warrant a change in the risks in the Petition's Risk Assessment.

Risk Distribution Issues

Most of the exposed populations have a dose that is lower than the dose of the RME individual. For example, most road construction workers are exposed to a dose of less than 110 mrem, thus the risk is lower than 0.5 in 10,000 (still assuming that the radium (226) concentration is 27 pCi/g).

Residents directly adjacent to the road (the RME individual) are calculated to have a risk of 0.08 in 10,000, which is much lower than the RME construction worker. Additionally, the dose (16 mrem) is only 0.2% of the background radiation dose of the resident adjacent to a road not using PG. Thus, the incremental risk above background from a road containing PG is very low. Dose (and, therefore, risk) decreases substantially as distance from the edge of the PG road increases (see Figure 2 below). As a result, residents whose houses are not adjacent to the PG road have essentially no incremental dose and risk.

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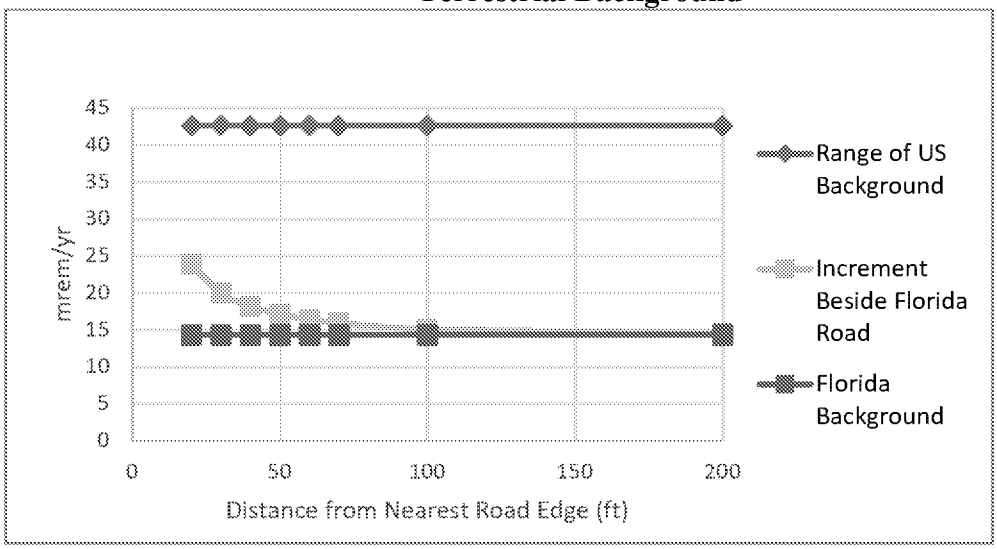
Figure 2: Incremental External Gamma Dose with Distance Compared to Terrestrial Background



(From Response to EPA Questions on January 16, 2020)
N.B.: All natural background (as used in Table 1 is higher than the Terresterial background utilized in this Figure).

<u>Uncertainties in RME Selection, Design and Average Radium (226) Concentrations</u>

The Petitioner's Risk Assessment and the Arcadis Response to EPA Comments on January 16, 2020 (Appendix 4a) compile and discuss in more detail the potential uncertainties in the risk assessment and the justification for the RMEs. For example, the design criteria used in the risk assessment were set at RME. The process of selecting the RMEs for this Petition was performed after evaluation of the road construction process and extensive pre-petition dialogue with EPA staff.

For example, TFI's consultant intentionally chose (and EPA staff tentatively accepted) a deterministic approach. A full probabilistic approach is resource intensive, but in this situation use of a reasonable maximum exposure (RME) and an explanation of the risk distribution achieves the same goal as a probabilistic approach (see Appendix 4a: Response to EPA Comments on January 16, 2020). The RME is one point on a probabilistic distribution (see conceptual figure provided below, Figure 3, which uses 90th percentile to illustrate the concept). EPA guidance does not dictate a particular percentile as an RME, e.g., the RME for the duration of living at home is 90th percentile, but some EPA risk assessments utilize lower percentiles depending upon the facts.

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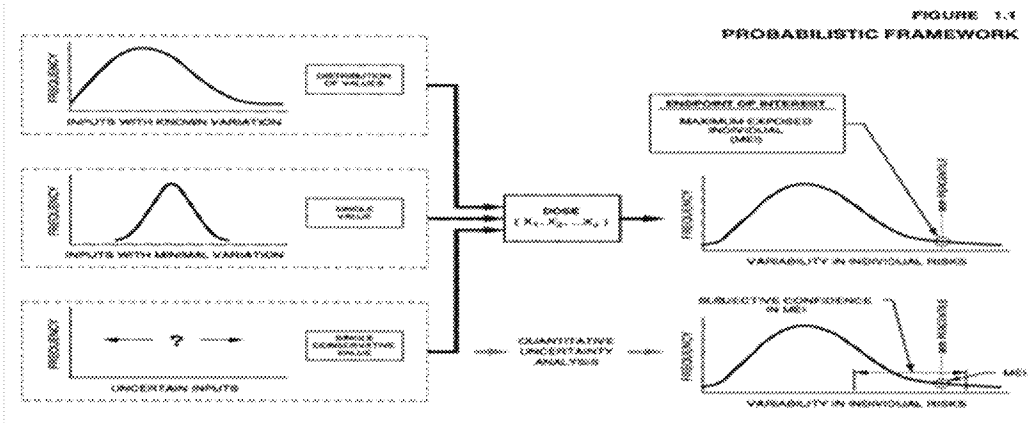
Figure 3: Conceptual Illustration of Probabilistic and Deterministic Frameworks



(This conceptual figure uses a 95th percentile to illustrate a high end exposure. But as noted in EPA guidance the assessor may derive a high-end estimate of exposure by using maximum or near maximum values for one or more sensitive exposure factors, leaving others at their mean value.)[33]

The Response to EPA Comments on January 16, 2020[34] describes in more detail the substantive rationale for the RME selections and the impact of variations in design factors.

For example, the Petitioner's Risk Assessment used a distance of 50 ft between roads and homes.[35] According to the Federal Highway Administration, the "new Interstate road needs a right-of-way width of 150 to 300 feet or more; a generation ago, roadbuilders could get by with 50 or 75 feet."[36] The larger the right of way, the lower the radiation level to residents.

Also, the Petition's Risk Assessment calculated the risk based on a road bed containing 50% PG and 50% soil. A 50:50 mixture of PG and local construction materials:

> "[I]s likely to be an overestimate of the actual mix. The EPA for example in their 1992 BID used a 1:2 mix of PG:sand. This is also the ratio in the Polk and Columbia county roads constructed by FIPR with input on the design and testing of the roads from the University of Miami and the Bureau of Materials & Research, the Florida Department of Transportation. This ratio is less than the ratio of two parts PG to one part soil utilized in EPA's 1992 BID risk assessment."[37]

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[33] Exposure Factors Handbook, *supra* note 11.

[34] Appendix 2 to this Petition is the same as the Petition's Risk Assessment (Petition's Risk Assessment). Appendix 4a addresses questions EPA raised concerning the original risk assessment (Response to EPA Comments on January 16, 2020).

[35] Petition's Risk Assessment at 3-2.

[36] Federal Highway Administration, Highway History, The Size of the Job, *available at* https://www.fhwa.dot.gov/infrastructure/50size.cfm.

[37] Petition's Risk Assessment, *supra* note 34, at 2-5 n. 9 and Response to EPA Comments on January 16, 2020, *supra* note 34, see answer to EPA question 5.

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Thus, EPA and other precedent accepts a 50-50 ratio as a RME. If the specific design for a particular road contains less than 50% PG then the risk is lower than the risk from RME.

Similarly, the concentration of radionuclides in concrete paving was assumed to be 2.25% PG, based on PG 15% by weight in cement and cement 15% by weight in concrete which is the same assumption utilized in the EPA 1992 BID risk assessment.[38] As a practical matter, the literature on the use of normal "gypsum" supports an upper limit of 15%.[39] If less than 15% PG is used, the average PG in the cement is less than 2.25% PG in surface pavement and the risk is lower than calculated in the Risk Assessment. Consistent with EPA policy, 50% PG for road base and 2.25% for surface pavement are appropriate RMEs. Also evaluated are the inevitable relatively slight variations in the risk potentially due to slight variations in the implementation of a 1 to 1 ratio of PG to soil in the road bed design standard (e.g., if the ratio 1.2 to 0.8 instead of 1 to 1) and the 2.25% PG in road surface design standard (e.g., if percentage of PG in the road surface is 2.7% instead of 2.25%). These variations in the input into the Risk Assessment do not significantly increase the risk. As noted above, various ratios of PG to soil were studied (from 100% sand to 100% PG) and all mixes had California Bearing Ratio values higher than sand or PG separately. See generally Appendix 4a.

As demonstrated in Appendix 4a, most of the other design features do not increase the level of radioactive emissions from the road. For example, the dose to a local resident adjacent to the road does not increase if the road has eight lanes or two lanes.

The data on the concentration of Radium-226 in the stacks (see summary above and more detailed discussions below in this Petition and in Appendix 5) are all well below the nominal concentration used in the risk assessment, therefore, the actual risk from PG use is likely to be well below the risk calculated in the Petition's Risk Assessment.

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[38] Petition's Risk Assessment, *supra* note 34, at 2-5.

[39] Since PG cannot be used in road construction in the U.S., the literature on PG is limited. However, the literature on the percentage of gypsum used in cement suggests that 15% is a reasonable number. For example, the "optimum addition of gypsum for Atbara clinker would be in the range of 3% to 5%." Amin Abdelrahman & Mohamad H. Aboud, Determination of Optimum Quantity of Raw Gypsum Addition for Atbara Cement Clinker, Khartoum University, 5, *available at* http://www.jeaconf.org/UploadedFiles/Document/82d8a051-43ad-44fa-ab1d-1ac182000608.pdf.

Similarly, the gypsum content of 5% in the composition of cement is referenced. *Available at* https://www.engr.psu.edu/ce/courses/ce584/concrete/library/construction/curing/composition%20of%20cement.htm.

Further, another article cites the use of 3% to 5% gypsum in cement. Karen L. Scrivener, Vanderley M. John, & Ellis M. Gartner, Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry, Cement and Concrete Research. Vol. 114, 2-26 (Dec. 2018), *available at* https://www.sciencedirect.com/science/article/pii/S0008884618301480?via%3Dihub.

There is a significant reduction in the split tensile strength at 15% phosphogypsum content. Thus the optimum amount of phosphogypsum in concrete is found to be 10%. Kuriakose Reju & P.K. Shaji, Effect Of Calcined Phosphogypsum In Portland Pozzolana Cement Concrete, International Research Journal of Engineering and Technology (IRJET) Vol. 05, Issue: 04, 2008 (Apr. 2018), *available at* https://pdfs.semanticscholar.org/d7cc/03c3de65ca412971fff244b37098d479d4ab.pdf.

All of the risk values in Table 1, above, are based on the RME assumptions and the assumption that the average radium (226) concentration in this PG is 27 pCi/g. The use of a radium (226) concentration of 27 pCi/g was chosen so that the submission contained a calculated risk which corresponds to a "nominal" concentration of radium (226).[40] Since the relationship of radium (226) concentration in PG to risk is proportional, the risk from using PG containing any other concentration of radium (226) in road construction can be calculated from the nominal concentration. Thus, a concentration of radium (226) in PG of 35 pCi/g (the radium (226) concentration proposed in the Second Revised Petition as the radium (226) concentration limit on PG used in road construction) can easily be calculated to be 0.65 in 10,000 (well below the risk management level used in the PG use guidance of 3 in 10,000). Conversely, the risk of 3 in 10,000 (EPA's safe risk level) corresponds to a radium (226) concentration in the order of 148 pCi/g (see this section and Sections III(G), V, V(D)(3,4), below). The discussion of the rationale for selecting a radium (226) concentration limit of 35 pCi/g is explained below

The use of 27 pCi/g is a reasonable value for the "nominal" radium (226) concentration given historic sampling of U.S. PG stacks and the average radium (226) concentrations utilized in the 1992 EPA BID risk assessment. However, TFI members sampled nine stacks located in four states in 2019.[41] The average radium (226) concentration of all 90 samples was 18.6 pCi/g with individual samples ranging from 6.3 pCi/g to 27.9 pCi/g.[42] The average concentration of radium (226) per PG stack ranged from 7.44 to 24.7 pCi/g (which is relevant because the PG for road construction use is likely to be from an individual stack). Within each stack sampled, the ratio of the highest to lowest measured concentration ranged from 1.2 to 3.7 pCi/g. These recent data found average stack radium (226) concentrations are well below the nominal concentration of 27 pCi/g used in the Petition's Risk Assessment, the 35 pCi/g concentration limit proposed in the Petition as the limit in the PG used in road construction, and significantly below the 148 pC/g corresponding to the 3 in 10,000 safe risk level.

If the average concentration of radium (226) per PG stack measured by TFI members (i.e., 4.77 to 24.7 pCi/g) is utilized in the risk assessment, the RME construction worker's risk from the PG used in road construction work ranges from about 0.09 in 10,000 to 0.5 in 10,000. Similarly, the risk to nearby residents directly adjacent to the road (the RME individual) is approximately 0.01 in 10,000 (1.4 in one million) to 0.7 in 10,000.

Given the range of individual concentrations in the historic and recent sampling of PG stacks and the variation within the stacks between the highest and lowest radium (226) concentration, it is exceedingly unlikely that the average concentration of radium (226) in any stack would be close to 148 pC/g. Thus, variations in radium (226) will not significantly increase the risk and, in any case, the PG limit is 35 pCi/g, well below the 3 in 10,000 safe risk level. Thus, EPA could approve use of PG from stacks without any sampling.

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[40] An average of 35 pCi/g also represents the highest average level identified in prior testing by EPA. To account for some potential variability (~30 percent) that has been observed in past testing, the relief sought in this petition seeks approval to use PG containing radioactivity levels of up to an average of 35 pCi/g in road construction materials.

[41] TFI, Supplement to the October 11, 2019 TFI Phosphogypsum Reuse Petition: 2019 Radium-226 Results for U.S. Phosphogympsum Stacks,1 (December 5, 2019) (TFI 2019 Sampling). Further discussion of this new data is provided below.

[42] *Id.* at 1.

The proposal in the 2019 Petition and this Second Revised Petition proposes annual sampling to provide continuing documentation that each shipment does not contain PG with an average radium (226) concentration above 35 pCi/g. The reasons for this suggested limit are as follows. First, a radium (226) concentration of 35 pCi/g is well below the radium (226) concentration of 148 pCi/g that corresponds to the 3 in 10,000 risk level (EPA's "safe" level). Thus, a maxium average concentration of radium (226) of 35 pCi/g is "safe." Second, TFI recognizes that EPA historically has utilized this regulatory approach so the likelihood of approval of the Revised Petition will be enhanced if the approval uses a maximum radium (226) concentration. Third, the requested limit of an average radium (226) of 35 pCi/g represents the highest average level identified in prior testing by EPA. Thus, this approach will make implementation more efficient. Fourth, an average radium (226) concentration of 35 pCi/g for PG used in road construction materials will account for some potential variability (~30 percent) that has been observed in past testing and during implementation of road construction. Finally, as more data is gathered over time during the implementation of this new use, TFI reserves to right to request EPA modify its approval to include a more efficient implementation approach.

The Response to the EPA Comments on January 16, 2020 performed a series of additional evaluations of the impact from the uncertainty in each of the exposure scenarios and found no significant increase in total risk, even when using the assumptions postulated in the EPA comments. In any case, the postulated assumptions are all less conservative than the RME scenario and did not warrant a change in the risks in the Petition's Risk Assessment.

Thus, consistent with the regulations governing EPA's approval of PG uses, the use of PG in road construction is safe and at least as protective as placement of phosphogypsum in a stack.

Table 2, below provides a summary of comments on risk distributions by exposure pathway. The table explains the limited applicability of the RME scenario and the potential for lower exposures and doses to occur for a broader population (taken from the Response to EPA Comments on January 16, 2020).

TABLE 2: SUMMARY OF RISK DISTRIBUTION FROM USE OF PG IN ROAD CONSTRUCTION

Exposure Scenarios	RME (small number of people)	Potential Lower Exposures and Risk Distribution
Road Construction Worker	Risk: 0.5 in 10,000 Few if any workers would fit the RME assumption of 100% of workdays on the uncovered road base. The RME worker is exposed to less than 7% of background levels (for all members of the public).	Much less than 0.5 in 10,000 Most workers are expected to spend less than 100% of the workday on the uncovered road base. Dose and risk reduce linearly with reduced exposure time. Time on a covered road base was shown in the Risk Assessment to be a factor of 5 lower. The dose would range down to essentially zero for management and supervision who would spend very limited time on the road and out of vehicles. The number of workers in a road crew is estimated to be as small as 6 – 8 workers, which limits the risk distribution to a small group.
Road User	Risk: 0.1 in 10,000	Well below 0.1 in 10,000

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TABLE 2: SUMMARY OF RISK DISTRIBUTION FROM USE OF PG IN ROAD CONSTRUCTION		
	This RME is assumed to be a heavy user of the road spending 2 hours daily on the road. This scenario is unlikely to occur until far into the future if PG roads become widely available. Until then it is unlikely a commuter would be able to spend this amount of time on a PG road. In the extreme case, the RME road user is exposed to less than 0.3% of background.	Most road users will be on the road for much less than two hours per day. Dose and risk reduce linearly with reduced exposure time. Initially when PG use in roads is newly implemented the availability of PG roads will be low reducing the opportunity to have substantive usage time. As the total amount of PG roads increase the risk distribution would increase with additional road users and cumulative usage time. The overall risk to an individual however, is not expected to exceed the RME estimates. Most road users would still have limited time on PG roads and this results in a proportionally limited dose and risk. The overall number of road users is difficult to specify as it depends on several factors including the road type and location relative to populated areas. However, the dose to road users would remain a small fraction of that from unavoidable background radiation.
Truck Driver	Risk: 0.5 in 10,000 The Truck Driver RME is limited to workers who participate in PG road construction projects. The assumptions for this scenario are set to estimate the upper end of likely dose and risk for this work. The RME Truck Driver is exposed to less than 6% of background levels.	A truck driver that has less than an RME exposure has lower risk than 0.5 in 10,000. There are a limited number of truck drivers involved in a road construction project. In addition, truck drivers will support numerous construction projects during the course of a year and many not involving use of PG. This limits the risk distribution for this exposure pathway to a relatively small number of people. In many cases, Truck Drivers will not work on PG road construction as much as assumed for the RME, resulting in a lower dose and risk.
Nearby Resident	Risk: 0.08 in 10,000 The Nearby Resident RME is based on extreme assumptions that are unlikely to apply to all residents of a PG road. The assumptions include close exposure to the road and long durations of residency throughout the exposure period. Based on these assumptions the Nearby Resident RME is exposed to 0.2% of background levels.	Most residents near a PG road would be exposed to much lower doses and risk, well below 0.08 in 10,000. Radiation levels from a PG road decrease rapidly with distance from the road and become indistinguishable from background at 50' to 100'. As a result, most residents immediately beside a PG road would be exposed to much less than the RME risk level, and residents beyond the immediately adjacent properties would experience essentially zero incremental risk. The overall risk distribution would depend on the overall length of the PG road and population density along the road but is limited to only those locations immediately beside the PG road.
Utility Worker	Risk: 0.004 in 10,000 The Utility Worker RME scenario represents an extreme case where a worker needs to disrupt the road for	Most Utility Workers would be exposed to risk much less than 0.004 in 10,000. Most utility repair requirements would involve exposure scenarios below those assumed for the RME conditions,

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TABLE 2: SUMMARY OF RISK DISTRIBUTION FROM USE OF PG IN ROAD CONSTRUCTION		
	road or utility maintenance. The assumptions use worst case conditions to estimate the risks and are limited to workers in a trench in a PG road and meeting the other exposure assumptions. The RME Utility Worker is exposed to approximately 0.3% of background levels.	due to smaller trenches and exposure areas, or shorter durations. The number of individuals entering a trench in a PG road is also limited based on the uniqueness of the work and the limited space. As a result, the risk distribution for the Utility Worker is limited to a small number of individuals.
Reclaimer Extreme Scenario	Reclaimer is an extreme scenario well beyond an RME assumption and therefore, is not appropriate to determine whether the use of PG is safe. This example for ultimate disposal was selected due to the use by EPA in 1992. Risk: 0.4 in 10,000 The Reclaimer would be exposed to approximately 1% of background levels. (total exposure of 78 mrem compared to a Background of 8,060 mrem over 26 years)	The Reclaimer scenario represents an extreme situation that is unlikely to even occur as described (Appendix 4b: Responses to Second Set of USEPA Questions - Reclaimer). As a result, the risk distribution is effectively zero. More realistic situations for the ultimate disposal of the road include continued use of the road as a road, or reuse of the PG road base for a new road, if the road was to be relocated or realigned. In the extreme case where a road is abandoned and then the land is reused for other purposes, the land preparation activities will realistically result in blending and mixing of the road base to levels that are indistinguishable from background levels. Overall, the risk distribution would be effectively zero.

In summary, the risk distribution from road construction is negligible, beyond the individuals who are on or immediately beside the road, as assessed in the Risk Assessment document. Thus, consistent with the regulations governing EPA's approval of beneficial uses, the use of PG in road construction is safe and at least as protective as placement of phosphogypsum in a stack. [43]

II. PETITION REQUEST AND LEGAL REVIEW PROCESS

A. Specific Relief Sought

This Petition requests the following:

[43] EPA's "assessment of the maximum individual lifetime risk of fatal cancer from radon emissions from stacks" was "less than three in ten thousand (3 x 10-4) to the maximally exposed individual." EPA, Applying to EPA for Approval of Other Uses of Phosphogypsum: Preparing and Submitting a Complete Petition Under 40 CFR 61.206: A Workbook, 5 (2005), *available at* https://www.epa.gov/sites/production/files/2015-05/documents/wrkbk_sub-r_appl_1105.pdf (EPA PG Workbook).

Therefore, "the risk assessment must demonstrate that the proposed other use will not cause a threat to the public or environment greater than if the phosphogypsum were left in the stack. This means that the risk assessment must show that the chance of developing a fatal cancer in people who are exposed to phosphogypsum as a result of the use for which you are applying must not be more than three in ten thousand (3×10^{-4})." *Id.* at 13.

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A determination by EPA, pursuant to 40 CFR § 61.206, that PG containing up to an average of 35 pCi/g may be used in road base, paving, and various combinations of road base and paving in Government Roadway Projects that meet the commitments of this petition and are:

1. Authorized by federal, state and local Departments of Transportation (DOT) or Public Works (PW), and

2. Conducted as part of a government road project using appropriate, generally accepted road construction standards and specifications such as ASTM, FHWA, federal or state DOT standards and specifications, or standards developed or approved in consultation with the appropriate regulatory DOT or PW authorities.[44]

B. Legal Review Process

1. Components of Petition

40 CFR § 61.206(b) provides the Petition must be in writing and should address the following topics:

- The name and address of the person(s) making the request.
- A description of the proposed use, including any handling and processing that the phosphogypsum will undergo.
- The location of each facility, including suite and/or building number, street, city, county, state, and zip code, where any use, handling, or processing of the phosphogypsum will take place.
- The mailing address of each facility where any use, handling, or processing of the phosphogypsum will take place, if different from paragraph (b) (3) of this section.
- The quantity of phosphogypsum to be used by each facility.
- The average concentration of radium-226 in the phosphogypsum to be used.
- A description of any measures which will be taken to prevent the uncontrolled release of phosphogypsum into the environment.
- An estimate of the maximum individual risk, risk distribution, and incidence associated with the proposed use, including the ultimate disposition of the phosphogypsum or any product in which the phosphogypsum is incorporated.

[44] There are 50 states and each has its highway design guidance documents. Federal and state transportation departments generally cite the Green Book, *supra* note 20. Attachment B contains representative examples of road way specifications (including alternative materials that may be used in road construction from Florida, Louisiana, Idaho, and North Carolina and the Green Book).

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- A description of the intended disposition of any unused phosphogypsum.

- The Petition must be "signed and dated by a corporate officer or public official in charge of the facility."

2. EPA's Determination and Risk Management Decision

The decision to approve a new use for PG must be made by EPA's Assistant Administrator for the Office of Air and Radiation (OAR). As a matter of policy, the decision involves weighing results of a risk assessment, technical analyses, and other factors.[45]

Section IV summarizes the Risk Analysis and metals screening evaluation that have been completed and demonstrate the safety of PG use in road construction. Key exposure and risk calculations and application of EPA's risk management criteria are described.

Section V provides TFI's justification for approval of this Petition and explains these factors as TFI submits they should apply to EPA's risk management decision. In conclusion, the road construction scenarios were evaluated for numerous risks (e.g., a broad scope of RME radiological exposures and non-radiological constituents present in PG). The analyses clearly demonstrate that:

- Use of PG in road construction presents no greater risk than stacking of the material; and

- PG can be safely used in road construction. In scientific terms, the use presents a risk of < 3 x 10,000, the level deemed by EPA to be safe (see discussion below).

3. Information and Certifications Required to Implement EPA Determination

Once the Assistant Administrator decides to approve use of PG in road construction under 40 C.F.R. 61.206(c), each of the reporting and records requirements at §§ 61.206(d) and 61.207-209 must be met. The only limitation on these requirements is that certain record-keeping obligations at § 61.209 may be waived. These reporting requirements include reporting the annual average radium-226 concentration at the removal location, and certification documenting purchaser, quantity and use information, along with a requirement that records must be retained for five years. These requirements ensure that EPA records contain information under §61.206(b) and in any event ensure that PG use and distribution is closely managed even where it is removed from a stack for an approved use.

[45] Basic concepts and definitions to aid the reader's understanding of the Petition can be found in Key Definitions which is a preamble to this Petition.

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III. REGULATORY HISTORY AND CHANGING CONDITIONS

A. Regulatory History

1. The Original 1989 NESHAP Rule

Prior to 1989, PG in the United States was used for beneficial purposes, such as constructing roadways and agricultural soil amendments. The 1989 NESHAP rule required that all PG must be placed in engineered above ground impoundments (commonly referred to as "gypstacks") or in phosphate mines where it can be used as backfill. 40 CFR § 61.202. EPA's 1989 regulatory analysis was based on an estimate of 66 stacks located in 12 states with two-thirds located in Florida, Texas, Illinois, and Louisiana.[46]

2. Post-1989 Regulatory Developments

After the issuance of the 1989 NESHAP rule, TFI petitioned for reconsideration. EPA agreed to reconsider that portion of subpart R that required that all PG be disposed in stacks or mines.[47] On June 3, 1992, EPA published a final rule approving PG use as an agricultural soil amendment and for indoor research and creating a framework for approving additional alternative uses.[48] In particular, EPA approved the use of PG as an agricultural soil amendment as long as the average concentration of radium-226 in the PG does not exceed 10 pCi/g (based on a maximum individual risk of 3 in 10,000 due to the use) and use of PG for research in amounts not to exceed 7,000 pounds. 40 CFR § 61.204-205.[49]

The amended regulations also allowed OAR to approve, on a case-by-case basis, a new use if it is as protective of public health, in both the short and long term, as disposal in a stack or a mine. 40 CFR § 61.206(a)-(c).[50] In 1992, EPA rejected the use of PG in road construction based on an analysis that assumed a roadway constructed with PG might be abandoned in the future, with a home constructed directly on top of the abandoned roadway with no site preparation (i.e., mixing). This hypothetical scenario included several extreme assumptions that resulted in unrealistic levels of exposure (i.e., it was not a RME).[51] For example, the 1992 EPA BID assumed a 70 year period for the duration of residential exposure for the hypothetical reclaimer exposure scenario even though the 1992 EPA BID used 25 years as the duration of a resident's exposure for the nearby resident. EPA's current RME for the duration of residential exposure is 26 years (a 90th percentile of exposure), precisely because "EPA has been criticized for too often

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[46] 1989 Rule, *supra* note 3.

[47] EPA; NESHAPS for Radionuclides Reconsideration; Phosphogypsum, 55 Fed. Reg. 13,480 (Apr. 10, 1990).

[48] EPA, National Emission Standards for Hazardous Air Pollutants; National Emissions Standards for Radon Emissions from Phosphogypsum Stacks, 57 Fed. Reg. 23,305 (June 3, 1992) (1992 Rule)

[49] *Id.* at 23,309, 23,311, 23,316. The volume of PG was increased by a later amendment.

[50] *Id.* at 23,319.

[51] *Id.* at 23,312.

assuming that future use will be residential" and other unrealistic assumptions.[52] Also see Appendix 4b: Responses to Second Set of USEPA Questions – Reclaimer.

3. Prior Petitions

On December 22, 2004, EPA "conditionally" approved the Petition of the Florida Institute of Phosphate Research (FIPR) to use PG as cover material in a demonstration landfill test cell project (discussions with EPA on this project were initiated in 2002 and the petition submitted December 9, 2003).[53] PG, however, was never used as cover material in a landfill test cell. As TFI understands it, by the time the petition was approved, conditions had changed and the landfill owner withdrew its request.

In 2010, Louisiana State University prepared a proposal to allow the use of PG testing to determine if PG could be used to make coastal zone protection devices.[54] TFI's understanding is that this effort proposal did not advance to the submittal of a petition.

These examples illustrate the unwieldiness of EPA's current approach to approvals for PG use. This has resulted in continued stacking, which has been subject to criticism as an unsustainable practice.

B. Factors Influencing Future Uses of PG

A number of factors influence the future uses of PG:

1. Current requirements to obtain regulatory approval prior to each individual new use slow the process of implementing beneficial, safe new uses. In many other countries, PG use is encouraged over storage and there are little or no regulatory restrictions on the use of PG up to an average radium (226) content of 27 pCi/g.[55]

2. The size, costs and complexity of gypstacks have increased (see, Appendix 6 Economic Analysis of Regulatory Costs Savings) well beyond original expectations. When the stacking solution was developed, two key factors were not fully recognized: (1) growth in the industry would result in a significant increase in the volume of PG material that would require storage capacity in stacks, and (2) the beneficial use for which PG could safely be employed. Today, active stacks are concentrated in Florida, Idaho, Louisiana, and North Carolina and contain at least 1.7 billion tons of stored PG. EPA's final rule did not anticipate the significant increase in production that would occur, creating a need for new storage capacity to handle the

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[52] EPA, EPA Land Use in the CERCLA Remedy Selection Process, OSWER Dir. No. 9355.7-04, 3 (May 25, 1995), *available at* https://www.epa.gov/sites/production/files/documents/landuse.pdf (Land Use in the CERCLA Remedy Selection Process).

[53] Holmstead FIRP Letter, *supra* note 7.

[54] Louisiana State University, Preparation of an Application for Approval to Use Stabilized Phosphogypsum as a Fill Material For Coastal Protection Devices, Final Report, Pub. No. 01-197-235 (Apr. 2010), *available at* http://fipr.state.fl.us/wp-content/uploads/2014/12/01-197-235Final.pdf.

[55] IFA Sustainable PG Management Report, *supra* note 12.

PG production rate of 46 million tons per year. As a result, EPA's 1989 final rule and its underlying analysis did not consider the full extent of present (and future) environmental impact and cost of long-term stack storage on a scale compatible with modern fertilizer production facilities.

3. Historically, EPA considered the radium-226 concentrations in individual phosphogypsum samples as ranging from 1.4 to 46 pCi/g.[56] At EPA's request, TFI members performed radiation sampling on gypstacks across the U.S. in 2019 to provide updated information (Appendix 5). Multiple stacks owned and operated by three companies were sampled (ten samples per stack were taken). The 2019 sampling found:[57]

- Radium (226) concentrations of individual PG samples ranged 6.3 to 27.9 pCi/g.
- The average radium (226) concentrations of all 90 PG samples from all stacks is 18.6 pCi/g.
- The average radium (226) concentrations per stack ranged from 7.46 pCi/g to 24.7 pCi/g. An EPA 1988 report states the mean concentrtions of radium (226) from Florida stacks ranged from 25 to 34 pCi/g.
- The average average radium (226) concentrations from PG samples taken from six Central Florida stacks is 19.6 pCi/g and for the Western US stacks is 15.8 pCi/g.
- Limited data reported in the literature on the concentrations of radium (226) in PG outside of the U.S. indicate that concentrations range from 6.7 pCi/g to 38.4 pCi/g, well below 148 pCi/g that corresponds to a risk of 3 in 10,000 (N.B.: Some data are average concentrations and others report as few as one sample).

The 2019 data demonstrate that the average radioactivity level for each stack is significantly lower than the 35 pCi/g radium (226) concentration limit requested in the Petition and less than 148 pCi/g which corresponds to EPA's safe risk level of 3 in 10,000. All of 2019 stack averages are below 27 pCi/g (the nominal concentration used in the risk assessment), thus, the risk for these stacks is below 0.5 in 10,000.[58]

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[56] EPA 1992 BID, *supra* note 15.

[57] TFI 2019 Sampling, *supra* note 41, at 1-5.

[58] The Risk Assessment found that the nominal level of radium (226) assumed for calculation purposes to be contained in PG (27 pCi/g) corresponds to a maximum risk of 0.5 in 10,000. Thus, the EPA PG risk management limit of 3 in 10,000 corresponds to a level of 148 pCi/g in PG (using the non-rounded risk for the construction worker). Therefore, PG may be safely used as road construction material.

4. The scientific community has developed an updated understanding of relative risks associated with PG.[59] This Petition has been prepared to enable EPA's regulatory decision to be based on the current, best scientific understanding of radiation protection and management related to PG use. The International Atomic Energy Agency (IAEA), an international organization which the U.S. helped establish to provide a scientific source of recommendations on radiation issues, has determined that radionuclide activity concentrations in PG material are less than 1 Bq per gram (Bq/g) (which corresponds to 27 pCi/g) "implying that it is not necessary to regulate."[60] Section IV below summarizes this updated understanding. U.S. and international research, as well as data from uses in developed nations, are now available to support various PG uses and demonstrate that PG use is at least as protective of public health as storage in stacks. More than a dozen beneficial uses have been analyzed worldwide, resulting in significant, successful PG use applications in at least 21 countries.[61]

Further, U.S. risk assessment approaches have changed based on experience and evolving environmental management policies since the 1980s, along with increased awareness of product lifecycles and sustainability. These changed conditions enable a more thorough and appropriate evaluation of PG use in road construction, and a demonstration that this use is protective of human health and the environment.

5. EPA policies encourage use and recovery of high-volume, low-risk waste. EPA's 1989[62] and 1992[63] risk management decisions concerning PG uses acknowledge, but do not provide, an effective mechanism to implement PG use decisions that are consistent with the Agency's overarching policy of supporting recycling. Since 1992, EPA has increased its emphasis on understanding product lifecycles and has adopted sustainability policies and encouraged sustainable practices.

6. The economics of gypstacks have changed. The cost to stack PG and manage gypstacks is increasing. These rising costs are a concern to U.S. phosphate fertilizer producers that must remain competitive in a global marketplace. Fertilizer companies outside the U.S. may use or sell for use their PG material safely utilizing the IAEA standards and avoid costs attendant to stacking. This puts U.S. companies at a significant economic disadvantage. The international community has actively moved in the direction of safe PG use and recycling, creating an increasing competitive

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[59] *See* International Atomic Energy Agency (IAEA), Radiation Protection and Management of NORM Residues in the Phosphate Industry, Safety Reports Series No. 78 (2013), *available at* https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1582_web.pdf (Radiation Protection and Management of NORM Residues).

[60] *Id.* at 56. This statement does not in any way preclude a risk based determination that higher levels might also be acceptable.

[61] IFA Sustainable PG Management Report, *supra* note 12.

[62] EPA, Comments and Response to Comments, NESHAP, National Emission Standards for Radon Emissions from Phosphogypsum Stacks, EPA-402-R-98-007, 3 (1998).

[63] 1992 Rule, *supra* note 48, at 23,306.

disadvantage for U.S. industry, particularly when one considers the costs associated with gypstack maintenance, closure, and long term care.

7. Perceptions of gypstacks have changed. EPA's final rule did not anticipate advese public sentiment from local stakeholders regarding the long-term presence of gypstacks, including aesthetic concerns. Some local governments and communities have expressed a preference for use of PG in a manner that encourages redevelopment of land currently utilized by and around gypstacks.[64] Such use increases economic development by generating jobs associated with the transportation and use of PG, and frees up land for other uses (Appendix 6).

8. TFI's proposal represents a significant regulatory burden reduction that will create new commercial markets, industries and jobs. This is in the context of the dramatic increase in PG use worldwide since 2008, from a baseline of close to zero to 35-40 million tons consumed worldwide by 2015.[65] To make comparable advancements, the U.S. phosphate industry, EPA approval of TFI's Petition would support the industry's sustainable development goals by expanding the list of PG beneficial uses and ameliorate substantial, avoidable regulatory burdens and costs imposed by the NESHAP Subpart R regulations.

IV. SUMMARY OF THE EVALUATIONS CONDUCTED FOR THE PETITION

A. Overview

EPA's document, titled "Applying to EPA for Approval of Other Uses of Phosphogypsum: Preparing and Submitting a Complete Petition under 40 CFR 61.206, A Workbook" (EPA PG Workbook) provides a guide for the Petition.[66] The key requirement expressed in this guidance (and the NESHAP) is that in responding to any proposed petition, EPA must decide whether the radiological risk associated with the alternative use poses no greater risk than placement in stacks.[67]

The decision concerning whether the radionuclide risk associated with PG in alternative uses is acceptable depends upon many risk analysis elements, including:

- The specific exposure scenarios that are determined to be appropriate. This Petition seeks approval of the use of PG in road construction based on a risk analysis for a series of specific exposure scenarios;

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[64] *See e.g., EPA holds meeting about Mississippi Phosphate Site*, St. Louis Post-Dispatch, Jan. 11, 2018, *available at* https://www.stltoday.com/news/world/epa-holds-meeting-about-mississippi-phosphate-site/html_0a41e1fa-96ef-54bb-a825-8fcaeb4b4463.html (comment of Pasagoula Mayor, Dane Maxwell, at an EPA public meeting regarding the Mississippi Phosphate site cleanup: "We want it clear and ready for development as soon as possible").

[65] *See* IFA Sustainable PG Management Report, *supra* note 12.

[66] EPA PG Workbook, *supra* note 43, at 13.

[67] *Id.* at 12.

- The RME exposure assumptions or parameters that are selected to estimate a high end radiation dose estimate during the alternative use of PG, i.e., an assumption likely to overestimate exposure. This Petition developed RME exposure assumptions for each exposure scenario and receptor based on high end construction design features that may affect the radiation dose and calculated a high end RME dose;

- The radiation dose to risk conversion factor used, see Attachment A;

- The cancer risk estimate based on RME exposure assumptions and the radiation dose to risk conversion factor of 5 in 10 million mrem;

- EPA's cancer risk limit for new PG uses of 3 in 10,000 during the use;

- A comparison of the estimated cancer risk to EPA's risk limit for new PG uses; and

- EPA's Risk Management Decision considering economic and other risk management factors.

EPA did not assess chemical risk from residual metals in its 1989 risk assessment or its 1992 risk assessment (which approved an agricultural use and denied approval to use PG for road construction).[68] In the 1992 EPA BID risk assessment, EPA stated that PG "contains some trace metals in concentrations which the EPA believes may pose a potential hazard to human health and the environment," particularly arsenic, lead, cadmium, chromium, fluoride, zinc, antimony, and copper.[69] The "trace metals also may be leached… and migrate to nearby surface and groundwater resources."[70] However, EPA explicitly decided in the 1992 EPA BID that these metals "will not be addressed in the risk assessment."[71] Thus, neither the 1992 EPA BID risk assessment for the approved use of PG as an agricultural amendment nor the 1992 risk assessment for use of PG in road construction (which was not approved) included a risk assessment or a screening level assessment for metals in PG.

For this Petition, however, EPA requested that TFI perform a risk screening level evaluation for the naturally-occurring radioactivity and metals. Although there is a question concerning whether EPA's NESHAP program has the legal authority to require an risk assessment of the impact of metals in PG used for road construction, TFI performed a high end exposure (i.e., RME or higher exposure) for the human health risk screening. That screening assessment concluded that the metals levels in PG are not expected to pose an unacceptable level of health risks to construction workers or cause an unacceptable impact in groundwater using PG in roadway construction. Thus, no further risk evaluation is warranted to assess risks from metals in PG used for road construction. Furthermore, proper construction practices employ BMPs such

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[68] EPA 1992 BID, *supra* note 15. 1992 Rule, *supra* note 48, at 23,305.

[69] EPA 1992 BID, *supra* note 15, at 2-8.

[70] *Id.*

[71] *Id.*

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as wetting surfaces to reduce dust formation, and these measures serve to further lower exposure. Studies and the nature of the petitioned PG use in road construction material compacted or encapsulated below pavement and above the water line indicate that leaching to groundwater (or surface water) is unlikely (ie., it is not a complete exposure pathway that warrants a more detailed risk assessment of the metals). The relevant Department of Transportation has responsibility to ensure that construction, using any construction materials (including PG), is to conduct construction activities in a manner that is protective of human health and the environment.

B. Exposure Scenarios

1. Overview

PG use was considered for road construction. This led to the development of the following RME exposure scenarios evaluated in the risk assessment:

- Road Construction Worker who builds roads exclusively with PG material for five years;
- Road User who routinely commutes on the constructed roadway by vehicle, motorcycle or bicycle for 26 years (motorist/bicyclist was deemed most conservative);
- Nearby Resident who lives in a home located 50 feet or more from a PG roadway for 26 years. To illustrate the amount of exposure reduction with distance, exposure to a resident who resides 20 feet from the PG roadway for 26 years was also calculated;
- Truck Driver who delivers PG for road base material to a construction site for five years; and
- Utility Worker who excavates across a PG roadway during utility maintenance projects and is exposed in a trench for 160 hours in a year.

These exposure scenarios were selected based on a review of prior regulatory submissions as well as discussions with EPA personnel, and the best professional judgment of the scientists assisting in the preparation of the Petition.[72] This analysis includes receptors not utilized by EPA in its 1992 BID risk assessment but added at EPA's request during the working sessions to fully evaluate public health.

This Petition also includes, at EPA's request, a hypothetical scenario which assumes a home is built upon an abandoned road constructed with PG (the so called Reclaimer scenario), which results in an extreme exposure (Extreme Reclaimer), i.e., the exposure is much higher than a RME exposure scenario. The probability of this scenario is very remote and implausible in that this construction scenario would likely never occur under existing road construction practices

[72] Arcadis (a firm specializing in design and consultancy for natural and built assets) and Exponent (an engineering and scientific consulting firm).

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and contraints on future land use for public infrastructure and therefore, the assumed scenario is not reasonably likely (Appendix 4b: Responses to Second Set of USEPA Questions - Reclaimer). Although this scenario also meets the EPA risk management limit of 3 in 10,000, it is not a reasonably likely scenario and therefore should not represent a condition of approval.

The design and construction of roadways is governed by policies and constraints on future land use associated with public infrastructure. The Reclaimer scenario of building a house on top of an abandoned roadway is not consistent with typical land re-use and sustainability policies, is limited by the legal constraints on abandoning public roads, is extremely rare (research has found few, if any, examples), and ignores the economic factors favoring using existing roads even if the land is being redeveloped. Therefore it is not a reasonably anticipated land use.

Nevertheless, EPA requested this evaluation to provide historical context for the 1992 EPA BID and confirm that this scenario is not a logical concern. This is discussed in further detail in Section IV (D)(9), below.

2. Reasonable Maximum Exposure (RME)

In order for there to be a risk, there must be exposure. EPA uses an RME metric to assess exposure risk. The "intent of the RME is to estimate a conservative exposure case (i.e., well above the average case) that is still within the range of possible exposures."[73] Each exposure factor used to estimate the RME should be selected "so that the resulting estimate of exposure is consistent with the higher end of the range of plausible exposures" (citing EPA's 1991 guidance).[74]

A National Academy of Science (NAS) Committee reviewing EPA's regulation of technologically enhanced naturally occurring radioactive material (TENORM) recommended that EPA "should use exposure and dose risk assessments that are 'reasonably realistic'" in developing standards for exposure to the various types of low level naturally occurring radiation.[75] "The Committee defined 'reasonably realistic' as 'not....intended to greatly overestimate or underestimate actual effects for the exposure situation of concern,'" and EPA agreed with the Committee's recommendations.[76]

The exposure calculations in the Petition use currently accepted radiation modeling methods such as RESRAD and MicroShield. State regulators, citing to EPA guidance, note that "if high-end values are chosen for every exposure factor, then the resulting exposure estimate may no longer be consistent with the RME and may exceed the realm of possibility altogether."[77]

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[73] EPA Risk Assessment Guidance for Superfund, *supra* note 10, at 7-1. *See also* ITRC, Decision Making at Contaminated Sites, *supra* note 10.

[74] *Id.* at 6.1.1.

[75] EPA, Report to Congress, Evaluation of EPA's Guidelines for Exposures to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), EPA 402-R-00-01, 15 (June 2000), *available at* https://www.epa.gov/sites/production/files/2015-04/documents/402-r-00-001.pdf (describing a National Academy of Sciences report on TENORM) (EPA Report to Congress Re: TENORM).

[76] *Id.*

[77] ITRC, Decision Making at Contaminated Sites, *supra* note 10, at 6.1.1.

The use of reasonable exposure assumptions is supported by the courts, which have long held that exposure assumptions "must bear some rational relationship" to actual conditions, and disallowed unduly conservative approaches. For example, a court rejected EPA's use of an extreme assumption - that a child eats sludge applied to roadside cemeteries every day for a five year period.[78]

Scenario-specific exposure assumptions were selected for this analysis in accordance with EPA guidance and methodology (see Table 3 below). These exposure assumptions are contained in appendices and accompanied by detailed scientific support, citations to guidance, discussion of best professional judgment and prior precedent used to make the selections. A summary of key exposure assumptions is provided in Table 3 below.

Table 3: Summary of Key Exposure Assumptions

Person	Description	Years	Model	Rationale
RME Scenarios				
Road Worker	Builds roads exclusively with PG material	5	RESRAD	The worker who uses PG to build a road is closest to the PG mixtures in road base and/or paving. Used Florida Department of Transportation construction project data and EPA guidance. Other road construction workers have lower exposure and therefore less risk.
Truck Driver	Delivers PG to the construction site to be used in road base and/or paving materials	5	MicroShield	A truck driver hauls PG to the road construction site for 5 years (the truck body provides some shielding).
Nearby Resident	Resident lives in a home located 50 feet or more from a road	26	MicroShield	EPA guidance on exposure values. To illustrate the amount of exposure reduction with distance, exposure to a resident who resides 20 feet from the PG roadway for 26 years was also calculated.
Road User	Resident drives on the road in a vehicle, or on a motorcycle or bicycle (the motorist/bicyclist is evaluated as the most conservative)	26	RESRAD	EPA guidance on exposure values.
Utility Worker	Worker in trench dug across a PG roadway (e.g., utility work)	160 days	MicroShield	Best professional judgment, based, in part, on limited time trenching occurs (since, among

[78] *Leather Indus. of America v. EPA*, 40 F.3d 392, 405 (D.C. Cir. 1994).

				other reasons, it obstructs traffic).

At EPA's request, the Petitioner provided a "reclaimer scenario" (an assessment of the extreme hypothetical exposure if the road is abandoned and a house is constructed on the abandoned roadbed (see Table 4)).

Table 4: Reclaimer Scenario Exposure Assumption (see the Petition's Risk Assessment and Appendix 4b: Responses to Second Set of USEPA Questions – Reclaimer)

Hypothetical Extreme Exposure Reclaimer Use Scenario				
Reclaimer Resident	Home constructed on an abandoned road	26	RESRAD (for gamma) Spreadsheet for radon	The abandonment of a road and construction of residential housing at the location is an extremely unlikely event included to evaluate the lifecycle and ultimate disposition of a PG road and is not a RME exposure. See discussion at Section IV(D)(9), below.

The RME is used to calculate the dose (i.e., the amount of radiation that the individual in the exposure scenario receives over a particular unit of time). In our situation, the annual and total doses depend on the length of time exposure occurs for that exposure scenario. Different exposure scenarios have different lengths of exposure. Risk is assumed to increase in direct proportion to the RME dose (i.e., if the RME dose increases by a factor of two, the risk increases by a factor of two).

The risk is then compared to the EPA risk management levels. EPA has long utilized (and courts have long upheld) the principle that a 1 in 10,000 risk level is "safe," although "[t]he upper boundary of the risk range [i.e., the 1 in 10,000 risk level] is not a discrete line." [79] As a unanimous *en banc* ruling of the Court of Appeals for the District of Columbia Circuit candidly noted, the basis for claiming harm from exposure to chemicals at extremely low environmental levels is more a function of "the rules of arithmetic rather than because of any knowledge" and there was "no particular reason to think that the actual line of the incidence of harm is represented" by the assumption selected by EPA.[80]

This acknowledgment is also apt for the risks from radionuclides. EPA's guidance for new uses of PG states unequivocally that for new PG uses to be approved, a petitioner must demonstrate that the cancer risk to those exposed to phosphogypsum as a result of proposed use "must not be

[79] EPA, Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions, OSWER DIRECTIVE 9355.0-30, 2 (Apr. 22, 1991), *available at* https://www.epa.gov/sites/production/files/2015-11/documents/baseline.pdf.

[80] *Natural Resources Defense Council, Inc. v. U.S. EPA*, 824 F.2d 1146, 1165 (D.C. Cir. 1987).

more than three in ten thousand" (i.e., 3 x10^{-4} or 3 in 10,000).[81] In the radionuclides NESHAP, EPA primarily, but not exclusively, evaluated the maximum individual risk (MIR) (which is the added chance of a cancer) and compared it to the NESHAP risk management level of 3 in 10,000.[82]

The use of the 3 in 10,000 "risk threshold is consistent with the determination of a 'safe' level first announced in the NESHAP for certain benzene source categories (54 FR 38044, September 13, 1989)."[83] As noted above, in the 1989 radionuclide rulemaking, EPA determined that six radionuclide source industries presented a cancer risk higher than 1 in 10,000 but that nonetheless was "essentially equivalent" to EPA's safe risk level "in light of the numerous uncertainties."[84] Similarly, EPA reaffirmed in 1992 that a 3 in 10,000 risk level was protective of human health and consistent with EPA's long-standing risk management goals.[85] In particular, EPA "determined" that the 3 in 10,000 risk level provided "an ample margin of safety, considering the cost, scientific uncertainty, and technological feasibility of control technologies needed to further reduce the radon emissions from [the PG] stacks."[86]

In summary, EPA explicitly has determined that the 3 in 10,000 cancer risk for radionuclides (including PG) is safe, consistent with overall EPA risk management policy. EPA has concluded that the "proposed other use will not cause a threat to the public or environment greater than if the phosphogypsum were stored in the stack," if the risk is not "more than three in ten thousand [3 in 10,000]."[87]

The relationship between exposure dose and risk is further elaborated on in Appendices 1 and 2.

C. International Commission of Radiological Protection (ICRP) Dose to Risk Relationship

The risk assessment selected in this Petition is the ICRP dose to risk conversion factor. The ICRP sets out the basis for evaluating health effects from radiological exposure along with recommendations for using specific values for regulatory purposes. While there are broad uncertainty bounds at low-dose exposures, the assumption of a linear relationship between exposure and risk is maintained regardless of the possibility of a threshold below which there is

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[81] EPA PG Workbook, *supra* note 43, at 13.

[82] 1989 Rule, *supra* note 3, at 51,654, 51,659, 51,660. In this context, the risk distribution (i.e. the range of risks to which the population is exposed) decreases as distance to the road increases, for PG use in road construction. Relatively quickly the dose falls below the dose that corresponds to background. The exposure to the residents is below the 3 in 10,000 safe level.

[83] EPA PG Workbook, *supra* note 43, at 5.

[84] 1989 Rule, *supra* note 3, at 51,654, 51,664, 51,666, 51,668-69, 51,677, 51,682. Risks ranged between 1 in 10,000 and 3 in 10,000. *Id.*

[85] 1992 Rule, *supra* note 48, at 23,305, 23,311-12, 23,316.

[86] EPA PG Workbook, *supra* note 43, at 5.

[87] *Id.* at 13.

no risk. In Publication 103, ICRP provides an analysis of the exposure values considered in that analysis. On the basis of model uncertainty and epidemiological evidence, the ICRP recommends a dose-to-risk coefficient of 5% per Sievert (one Sievert is equivalent to 100 rems or 100,000 mrem, see explanation of terms in Attachment A).[88] This coefficient is the basis for current international radiation safety standards, and is considered by ICRP to be "appropriate for the purposes of radiological protection." Although it is based on cancer mortality as the endpoint, it is also approximate for all calculated detrimental effects.

For our risk analysis, we use a dose conversion expressed in terms of millirems or mrem.[89] Translating the 5% risk per Sievert recommended by the ICRP for regulatory purposes yields 5 x 10^{-7} risk per mrem.

The risk assessment submitted as part of this Petition estimates the annual dose for each of the exposure scenarios, summed over the associated years of exposure, to provide a total dose that is then converted to a cancer risk using a dose-to-risk conversion factor of 5×10^{-7} risk per mrem (i.e., 5/10,000,000).

Our use of 5 x 10^{-7} as a conversion factor is consistent with EPA risk assessment procedures.[90] The EPA's 2011 guidance provides cancer risk factors for uniform whole-body exposures of low-dose gamma radiation to the entire population, and reports an estimated 90% confidence interval for cancer mortality of 2.8% to 10% per Gy[91] (i.e., from 2.8 x 10^{-7} to 10 x 10^{-7} per mrem).[92] This range is essentially the same dose to risk conversion range derived by ICRP.

The value we use is also consistent with the perspective of the National Council on Radiation Protection and Measurements (NCRP) (the U.S. organization chartered by the U.S. Congress in 1964 to, among other things, "develop … recommendations about …protection against radiation" (i.e., NCRP uses the same dose to risk conversion factor as in the 2007 ICRP)).[93]

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[88] International Commission on Radiological Protection (ICRP), The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, 55, 87 (2007), *available at* https://www.icrp.org/publication.asp?id=ICRP%20Publication%20103 (2007 ICRP Recommendations).

[89] The mrem is a common unit of radiation dose. In this report, "dose" refers to effective dose, which simply means that when a person is exposed to a uniform radiation (e.g., external gamma radiation), all of the doses to the different organs are weighted by their radiosensitivity and added together. See Appendices 1 and 2 for more detailed discussion of the definitions and application of these factors.

[90] Similarly, the international community has widely adopted the International Atomic Energy Agency (IAEA) determination that 1 millisievert (1 mSv) per year is the acceptable level of radiation exposure (for example, the European Union [EU] regulations). *See* Radiation Protection and Management of NORM Residues, *supra* note 59, at 165. The IAEA and EU determinations are also based on the International Commission on Radiological Protection. 2007 ICRP Recommendations, *supra* note 88, at 55, 97, Table 5, 116, and Table 8.

[91] For practical purposes as to gamma radiation, 1 Gy = 1 Sv = 100 rem = 100,000 mrem.

[92] EPA, EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population, EPA 402-R-11-001 (April 2011), available at https://www.epa.gov/radiation/epa-radiogenic-cancer-risk-models-and-projections-us-population (EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population),

[93] National Council on Radiation Protection and Measurements, Management of Exposure to Ionizing Radiation: Radiation Protection Guidance for the United States, NCRP Report No. 180, 42 (2018), *available at* https://ncrponline.org/shop/reports/report-no-180-management-of-exposure-to-ionizing-radiation-radiation-protection-guidance-for-the-united-states-2018-2018/ (Management of Exposure to Ionizing Radiation).

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The ICRP analysis was also relied upon by the European Union (EU) in selecting its general population acceptable dose level.[94] The EU appointed a group of experts to provide advice on the basic safety standards, taking into account the 2007 recommendations of the ICRP (specifically, ICRP Publication 103 since the ICRP reflected "new scientific evidence and operational experience").[95]

The most recent report of the NCRP (2018) (Report No. 180) provides a detailed discussion of the risks from exposure to ionizing radiation and states that "[*t]he value of 5 % Sv*$^{-1}$ [i.e., 5/10,000,000 per mrem] *is a rounded value for radiation detriment used to inform all the NCRP recommendations regarding stochastic effects*,"[96] (emphasis added).

In summary, the use of the ICRP dose to risk relationship is scientifically sound and supported by many independent governmental entities, including EPA and NCRP. We elaborate further in Appendices 1 and 2. The "conservative" nature of the assumptions underlying the dose to risk relationship and associated uncertainties are discussed below.

For the reasons noted above, the risk estimates derived for PG using the ICRP dose to risk conversion factor are based on a linear relationship between dose and risk for the very low dose exposures derived for this report. Therefore, they are appropriate for use in the Petition and can be relied upon by EPA in its decision making.

D. Calculation of Risk that Corresponds to the RME

This section summarizes the RME doses calculated in the Risk Assessment and explains generally how they are derived.

1. Deriving Dose for the Period of Use

A dose is the cumulative amount of radioactivity absorbed (weighted to take into account the different medical impacts of different types of radiation). The dose is calculated using the RME associated with each scenario.

Duration is specific to the exposure scenario. For a resident, the exposure period is 26 years based on standard EPA guidance.[97] For a road construction worker, the length of exposure is

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[94] ICRP is an international expert advisory body that offers its recommendations to regulatory and advisory agencies, mainly by providing guidance on the fundamental principles on which appropriate radiological protection is based. The 2007 recommendation was produced "after eight years of discussions, involving scientists, regulators, and users all around the world." 2007 ICRP Recommendations, *supra* note 88, at 3.

[95] Official Journal of the European Union, Council Directive 2013/59/Euratom, 4 (Dec. 5, 2013), *available at* http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2014:013:FULL&from=EN. L 13/2 COUNCIL DIRECTIVE 2013/59/EURATOM (setting forth basic safety standards for protection against the dangers arising from exposure to ionizing radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom) (Council Directive 2013/59/Euratom).

[96] Management of Exposure to Ionizing Radiation, *supra* note 93.

[97] 26 year exposure duration for residence – 90th percentile recommended by EPA. EPA, Human Health Evaluation Manual, Supplemental Guidance: Update of Standard Default Exposure Factors, OSWER Directive 9200.1-120

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five years (based on data from roadway construction projects, DOT manuals, and EPA guidance (see Petition's Risk Assessment (Appendix 2) and discussed in more detail in Appendix 4a: Response to EPA Comments on January 16, 2020, and below in this Petition, Section V). The risk assessment determined that the 3 in 10,000 risk level corresponded to a total cumulative dose of 600 mrem and this value can be used to judge the magnitudes of exposure for each scenario. Table 5 below summarizes the exposure doses calculated in the risk assessment on an annual and scenario basis.

Table 5: Total Dose Summary

Person Exposed	Annual Dose	Years	Total Use Exposure Dose (mrem)
Road Worker	22 mrem	5	110
Truck Driver	18.6 mrem	5	93
Nearby Resident	multiple exposures over 26 years	26	16
Road User	1 mrem	26	28
Utility Worker	0.8	160 hours in 1 year	0.8

2. Converting the Total Use Dose to Risk

Radiation risk for cancer is calculated as the product of the RME exposure dose for each scenario and the dose-to-risk conversion factor. The distance from the road and durations of exposure are key considerations in calculating the total dose risk. While the RME is designed to bound these, most residents would be located at greater distances from the road and/or experience shorter durations of exposure than the RME individual. Thus, actual doses for the populations would be less than those presented here.

As noted above, using a dose-to-risk conversion factor of $5x10^{-7}$ risk per mrem, 600 mrem corresponds to a 3 in 10,000 risk level. From this relationship, one can calculate the risk for a particular dose. The result of the risk calculations are summarized in Table 6 below. The results of the calculations are provided in Appendices 1 and 2 of this Petition.

Table 6: Total Use Dose and Risk Table Compared to Background

RME Exposure Scenario	Total Use Dose (mrem)	Years	Risk From the Use
Road Construction Worker	110	5	0.5 in 10,000
Truck Driver	93	5	0.5 in 10,000
Road User	28	26	0.1 in 10,000
Nearby Resident	16	26	0.08 in 10,000
Utility Worker	0.8	160 hours in 1 year	0.004 in 10,000

(Feb. 6, 2014), *available at* https://www.epa.gov/sites/production/files/2015-11/documents/oswer_directive_9200.1-120_exposurefactors_corrected2.pdf (Update of Standard Default Exposure Factors).

3. Road Construction Worker Risk

Based on the assessments provided in this Petition, the highest estimated RME exposure is for the road construction worker placing road base containing PG that contains radium -226 at 27 picocuries per gram. The exposure dose amounts to ~22 mrem/year (which results in a 110 mrem total dose for the exposure period of five years). This dose corresponds approximately to an incremental cancer risk of 0.5 in 10,000, which is over 5 times less than the PG use risk management level of 3 in 10,000.

4. Risk to the Nearby Resident

In addition to the highest risk individual (a road construction worker), the risk assessment also evaluated the exposure doses and risk to a resident who may live immediately adjacent to the road. Consideration was given to all stages of life from childhood through adult. Exposure depends on distance, with exposures dropping off quickly as distance from the road increases. Nevertheless, for people living immediately adjacent to the road, the exposures and risks are well below the risk management level of 3 in 10,000.

The exposure doses and risks were estimated without considering shielding during the period of construction; shielding was included when estimating doses following construction of the road. Shielding of residents was afforded by the road surface as well as by embankments and other structures that cover the sides of the road base.

The cumulative incremental dose associated with living in a house adjacent to a road with a PG base is 16 mrem and the associated risk is 0.08 in 10,000. These RME exposure dose and risk estimates to nearby residents are well below the EPA risk management levels.

5. RME Risk from the Other Exposure Scenarios

Doses and associated risks for all other RME exposure scenarios (the truck driver delivering the PG, the users of the road, and the utility worker in a trench near the road) are lower than those for the road construction worker (see Table 1 and 6).

6. RME Exposures/Risks, by Definition, are the Highest Exposures

All exposure scenarios have doses and risks that are less than the EPA's risk management levels. The RME risks are constructed to overestimate rather than underestimate the actual risks and this provides confidence for making decisions that are health protective.

Other workers who are more distant from the PG have lower exposures than the construction worker (and, therefore, lower risk). Similarly, most residents living near roadways are exposed to lower risk levels and most PG will contain lower radiation levels used in this calculation. Moreover, the dominant source of dose is gamma radiation which decreases with distance and hence, residents who live more than 50 feet from a road will receive a lower dose (and consequent risk) than the RME at a distance of 50 feet from the edge of the road.

A summary of the risk distribution provided in Table 2, above (which is from Appendix 4a).

In summary, the risk distribution from road construction is negligible, beyond the individuals who are on or immediately beside the road, as assessed in the Risk Assessment document.

7. Comparison to Background

Because radiation is always present naturally, it is helpful to compare the incremental radiological exposures to background levels to provide important perspective. While natural background varies geographically (between states and even within states), a value of approximately 310 mrem a year was used for comparison because it is a widely used national background level. Background radiation varies naturally from ~100 mrem to 1,000 mrem. Thus, the ratio of total use exposure to background will vary depending upon the location of the road (see Table 1 below and provided above). Given the conservative nature of the exposure estimates, these incremental exposures would likely be within the variability of measurement for ambient radiation.

Table 1: Dose, Risk, and Background Summary for All RME Scenarios (repeated for the convenience of the reader)

Receptor	Site	Exposure Duration (years)	Exposure Dose (mrem)	Estimated Cancer Risk	Background Dose from Exposure Duration (mrem)	Exposure Dose Percentage of Background Dose (%)
Reasonable Maximum Exposure Scenarios						
Road Construction Worker	PG in Road Base	5	110	0.5 in 10,000	1550	7%
Road User (Motorist/Bicyclist)	PG in Road Base & Surface	26	28	0.1 in 10,000	8060	0.3%
Truck Driver	PG-containing material for Road Base	5	93	0.5 in 10,000	1550	6%
Nearby Resident	PG in Road Base & Surface	26	16	0.08 in 10,000	8060	0.2%
Utility Worker	PG in Road Base	1	0.8	0.004 in 10,000	310	0.3%
	EPA Cancer Risk Management Goal		600	3 in 10,000	600	

Estimated cancer risk below this goal.

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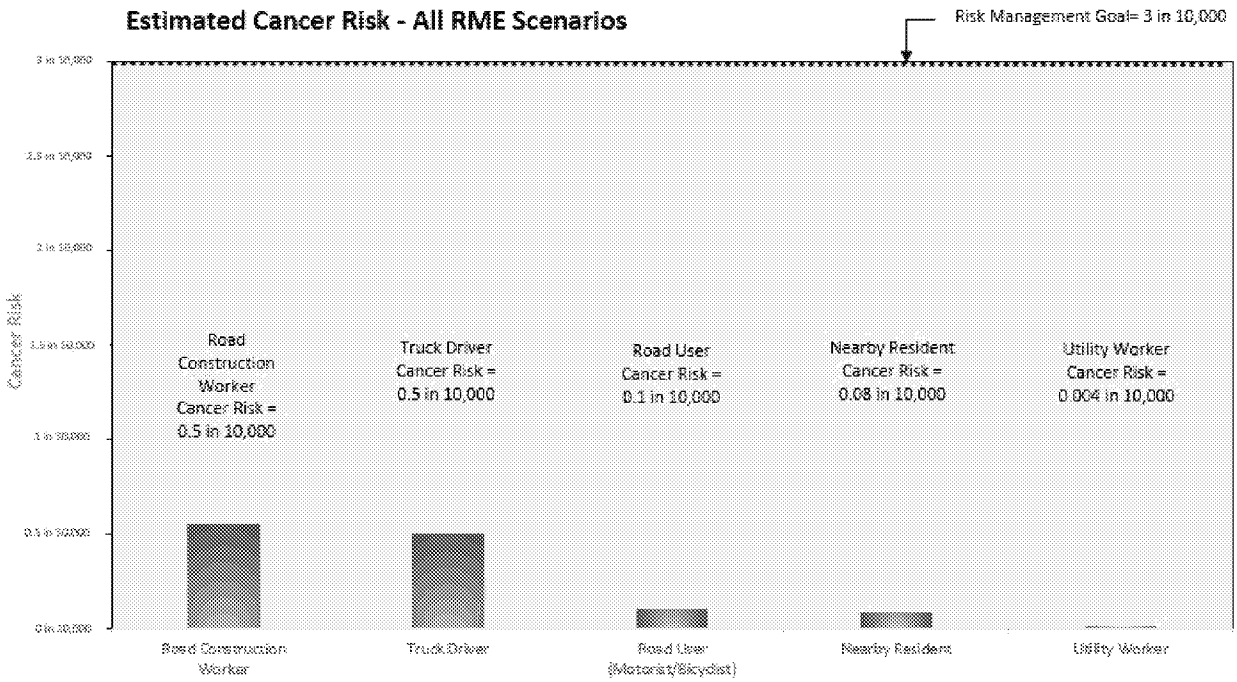
Figure 4: Estimated Cancer Risks



8. Disposition Scenario

The EPA PG use regulations require an assessment of the risk from the ultimate disposition of PG for any product in which the PG is incorporated.[98] The RME for the ultimate disposition of a new road constructed with PG is that it serves as an established part of municipal (county, state, or federal) infrastructure and as such would require periodic repair and expansion as needed. Road maintenance activities include removing the surface, grinding and reusing or disposing of the materials consistent with federal, state, and local regulations. Exposures and risks associated with maintenance of roads and reuse of construction materials are expected to be comparable to or less than those detailed in the risk assessment for road construction (Appendix 4a: Response to EPA Comments on January 16, 2020).

9. Extreme Hypothetical Reclaimer Requested By EPA (> RME)

Our evaluation is that, in light of current policies and known constraints on future land use for public infrastructure, a hypothetical reclaimer scenario does not represent a reasonably foreseeable future use for inclusion in the risk analysis for this Petition (Appendix 4b: Responses to Second Set of USEPA Questions - Reclaimer).[99]

The reclaimer scenario used in the 1992 BID Risk Assessment as a reasonable disposition scenario (without any explanation or scientific support) was the assumption that a house is built

[98] 40 C.F.R. § 61.206 (a)(8)(1).

[99] Memorandum from TFI to Lee Veal, Director, Radiation Protection Division, U.S. Environmental Protection Agency (April 24, 2019). This detailed memorandum explains the reasons that the Reclaimer Exposure Scenario is not a RME.

on the roadbed at some future time after the road is closed and the road surface has crumbled and been removed. (EPA 1992 BID, p. 4-10). This was not an RME disposition scenario then, nor is it realistic now.

First, a diligent search has not found any documentation of paved roads being abandoned and residential housing being constructed immediately on the abandoned pavement.[100]

If there are any examples, they are rare (i.e., 90th percentile or above) and beyond the RME exposure.

Second, there are many institutional and legal obstacles to abandoning roads, much less constructing homes on them. All public roadways and associated rights of way are owned and operated by the government and by law are dedicated to public use. All of these public roadways are subject to governmental jurisdiction with zoning and land use requirements that support continued roadway use. For example, to abandon a road in Florida, there must be notice of the intent to abandon the road, a public hearing, a duly adopted and entered resolution of abandonment, and notice of the abandonment resolution.[101] A road cannot be abandoned if it is a public road and is used by the public (see Florida, Idaho, Louisiana, Alabama and several other state laws). Some states, such as Alabama, have a statutory preference against abandonment. Federal highways can be decommissioned, consistent with a robust public process. In the case of the Pennsylvania Turnpike, part of it was converted to a bike path.[102] Similarly, the West Side highway in New York City was converted into an urban park, not housing. In any event, roads built with PG will be constructed and and maintained consistent with state and federal laws. Any effort to abandon and repurpose these roads, including for development, also must be consistent with federal and state statutes and local ordinances.

Similarly, some county roads are abandoned to become state roads and some state roads are abandoned to become federal roads. Transfer of a state road to the federal highway system or vice a versa is not relevant since the road remains a road.

Maintaining public roadways and associated rights of way into the future is consistent with current trends in community plans to maintain and expand roadway infrastructure and utility services (buried within right of ways) and to provide access (e.g., ingress/egress to surrounding parcels). Converting a roadway to a residential property must be done consistent with state laws and would complicate or eliminate access to surrounding parcels in addition to the redeveloped residential property[103] and is not a realistic assumption. Furthermore "[v]acating a road that

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[100] Abandonment of unpaved roads is not relevant since we are not seeking to approve of the use of PG on unpaved roads. This factor and the other factors in the text are summarized from the Petition's Risk Assessment (Appendix 2), Responses to Second Set of USEPA Questions – Reclaimer (Appendix 4b), and the legal research on the legal obstacles on abandonment of roads provided in the Revised Petition.

[101] Fla. Stat. § 336.10. *See* 23 C.F.R. § 620B.

[102] *Abandoned Stretch of Turnpike in PA*, ConstructionEquipmentGuide.com, Jan. 11, 2006, *available at* https://www.constructionequipmentguide.com/redirect/6495?story=6495.

[103] *See* James J. Fazzalaro, Local Road Abandonment and Abutting Property Owners, OLR Research Report, 2003-R-0897 (December 24, 2003), *available at* https://www.cga.ct.gov/2003/olrdata/tra/rpt/2003-R-0897.htm.

eliminates or substantially diminishes access for abutting property owners may likely amount to a taking,"[104] which is another disincentive to abandonment.

Third, economics dictates that if an abandoned road is transferred to a housing association, the land will remain as a road maintained by the housing association. More generally, since storm drains and often utility lines are placed along rights of way, the abandoned road is more likely to be used as a private road, not housing. While it is not impossible for a house to be be built on an abandoned roadway, it is certain to be extremely rare.

Fourth, the sustainability of roads and the use of road construction materials are key aspects of guidance and plans for roads under the jurisdictions of the Federal Highway Administration and state Departments of Transportation. The in-place abandonment of municipal infrastructure and allowance for construction of residences on top of these abandoned roads runs counter to sustainable infrastructure projects involving road construction. In any case, the construction activities required for road maintenance result in less exposure than during the original road construction (i.e., the construction activities on scale).

Thus, road abandonment, and the construction of a home on the abandoned road is not an RME exposure and, therefore, is not an ultimate disposition scenario. The fact that this extreme exposure scenario corresponds to a risk below the EPA risk management level confirms that the lesser exposure in the ultimate disposition scenario need not include a numerical risk assessment.

Finally, normally, the removal of unused PG during the road construction project is not an appropriate ultimate disposition because from an economic perspective, it is unreasonable to purchase more PG than will be used. Appropriate planning will ensure that all PG is mixed with soil (in a one to one ratio) and used in the road. In the rare case where there is unused PG, it can be used in another ongoing road construction project or returned to the PG source to be stored on a PG stack. Thus, a Reclaimer Exposure Scenario should not be utilized to determine whether to approve the use of PG for road construction.[105]

But, since EPA requested that the risk analysis include the extreme hypothetical reclaimer scenario, it is summarized below (see Petition's Risk Assessment and Appendix 4b: Responses

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Florida Office of the Attorney General, Counties, roads and streets, dedication, vacation, Advisory Legal Opinion – AGO 78-118 (Sep. 27, 1978), *available at* http://www.myfloridalegal.com/ago.nsf/Opinions/1F43FA7B5F1C0AF18525659300627D32. Association of County Commissions of Alabama, Acceptance, Annexation and Vacation of County Roads (May 11, 2016), *available at* https://www.alabamacounties.org/sdm_downloads/creation-acceptance-annexation-and-vacation-of-county-roads/.

[104] Thomas Ruppert, Erin Deady, Jason M. Evans, & Crystal Goodson, Legal Issues When Managing Public Roads Affected by Sea Level Rise: Florida, 5 (Spring 2019), *available at* https://www.researchgate.net/publication/332528839_Legal_Issues_When_Managing_Public_Roads_Affected_by_Sea_Level_Rise_Florida.

[105] As a practical matter, if a risk assessment uses extreme enough assumptions, the calculated risk will exceed any risk management safe level. Thus, realistic but high-end RME are used.

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to Second Set of USEPA Questions – Reclaimer, which responds to the technical issues relating to the extreme Reclaimer scenario). As part of the hypothetical reclaimer scenario, the exposure assumptions still need to be RME assumptions. The duration of exposure is 26 years (because that is EPA's RME residential exposure (i.e., the 90th percentile of exposure)).[106] Normal house construction practices were utilized, such as use of non-PG fill to grade the land (which mixes the PG with non-PG soil), the use of vapor barriers and a slab beneath the house, and the like (as described in Appendix 4a: Response to EPA Comments). The annual total radiation dose is 3 mrem, which converts to 78 mrem over 26 years (the total use dose). The resident reclaimer scenario requested by EPA is an extreme exposure duration. Nonetheless, this risk (which is higher than an RME risk) corresponds to about a 0.4 in 10,000 risk, still below the PG use risk management level of 3 in 10,000.

Even this extreme hypothetical scenario does not result in exposures and risks that exceed the EPA risk management level of 3 in 10,000. It must be emphasized that the use of the reclaimer scenario does not mean it is a foreseeable ultimate disposition. In any event, the fact that this extreme exposure scenario presents a risk below 3 in 10,000 demonstrates that any conceivable RME scenario related to ultimate disposition will meet the EPA's risk management level.

E. Groundwater Pathway Screening Analysis

EPA's PG Petition guidance suggests that the Petition should address other potential pathways of exposure, such as the ground water pathway, if they are relevant.[107] The Petition used a screening analysis to address these pathways and, where appropriate, referenced EPA's prior evaluations. A conservative screening level analysis generally is used to determine at an early stage that no further analysis is warranted.

1. Radionuclides in Groundwater

EPA performed extensive modeling of the likely migration of radionuclides in a 1992 assessment of the risk from PG used in agriculture and road construction. Neither concluded that the groundwater pathway supported restrictions on the use of PG.[108] EPA's risk assessment determined in 1992 that "no radionuclides are calculated to reach the onsite well via the groundwater pathway" nor are any "radionuclide calculated to reach the off-site river or well via groundwater."[109] (see SENES 1997[110] which also examined the potential for impacts to

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[106] 90th percentile exposure means that 90% of the exposed population has that level of exposure or less and only 10% of the population has higher exposure. EPA published its Superfund Land Use Directive in 1995 (Land Use in the CERCLA Remedy Selection Process, *supra* note 52) and reaffirmed the policy in 2001 (EPA, Reuse Assessments: A Tool To Implement The Superfund Land Use Directive, OSWER 9355.7 - 06P (June 4, 2001), *available at* https://nepis.epa.gov). EPA's 1995 Land Use Directive acknowledges that "EPA has been criticized for too often assuming that future use will be residential" and identifies several evaluation factors to identify reasonably anticipated future land use, such as current land use, zoning laws and maps, community master planning, population growth patterns and projections, accessibility to existing infrastructure, site location, federal/state land use designation, and others.

[107] EPA PG Workbook, *supra* note 43, at 10.

[108] EPA 1992 BID, *supra* note 15, at Chp 4. See discussion in Appendix 2.

[109] EPA 1992 BID, *supra* note 15, at 4-31, 4-34, Scenario 8, Tables 4-5, 4-18, n. C, Scenario 11, among other sources.

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groundwater and surface water pathways). These studies found no realistic potential for impacts to these pathways, i.e.:

> No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.[111]

The radionuclide risks were found to be negligible. The TFI consultants agree with these prior assessments and no additional evaluation was deemed necessary. No monitoring data reviewed indicates significant groundwater impact from radionuclides. The Response to EPA Comments on January 16, 2020 (Appendix 4a) provides a more detailed explanation of the extremely low risks from radionuclides in groundwater, which was the basis from the Petition's Risk Assessment not duplicating these conservative calculations.

2. Screening Evaluation of the Potential Impact of Non-Radionuclides in PG

The EPA PG Guidance states:

> [A petitioner] "must provide information on the other toxic or hazardous constituents of the waste…to assure that the proposed use does not cause non-radiological risks to human health and the environment."[112]
>
> To the extent the phosphogypsum is land applied or will remain in place following the test, the risk assessment must examine other potential pathways of exposure, in particular with respect to ground-water and surface water. Consideration of multiple pathways, particularly pathways associated with ground water, are consistent with our review of alternative uses as found in the 1992 rulemaking on phosphogypsum.[113]

Despite this, EPA did not include an assessment of the impact of metals in its review of alternative uses of PG in 1989 or 1992 (see Appendix 3).

However, EPA requested that TFI perform screening analyses of the potential impact of direct contact with PG by road construction workers, and evaluate potential metals leaching on ground and surface water quality. Thus, these assessments were performed and appear in Appendix 3.

These analyses confirm that PG is "safe" for worker handling with respect to non-radionucldes as well. Road construction workers were assumed to come into direct contact with PG (incidental ingestion, inhalation, and dermal contact). The PG concentrations were then compared to health-based screening levels. The chemicals in PG were found to be either a low risk or present at background levels.

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[110] SENES Consultants Limited, Application for Exemption – For Use of PG in the Construction of Thornhill Road, Polk County Florida (Draft), Prepared for the Florida Institute of Phosphate Research (1997).

[111] EPA 1992 BID, *supra* note 15, at Chp 4, Note C, Table 4.15.

[112] EPA PG Workbook, *supra* note 43, at 9.

[113] *Id.* at 12.

Appendix 3 contains an assessment of the potential for metals to leach from a roadbed using PG. The design of new roads affects the potential for exposures by creating a degree of isolation of the base layer from the environment. The PG in the proposed alternative use is placed above the water table and underneath the road's paved surface. Additionally, the roads are sloped to drain precipitation.[114] This further limits water contact with the PG isolated within the base layer. Thus, for purposes of the Petition, leaching of PG to groundwater or surface water is likely not a complete exposure pathway of concern for roadbed use and therefore no more detailed risk assessment is needed based on the typical screening level approach.

The metals concentration in the road base (and, therefore, the amount that is leached) is only 50% of the concentration of metals in PG because the PG is mixed with soil, sand, or aggregate (see Appendix 3).

The literature shows limited leaching directly from PG. For example, a 2011 University of Florida study by Mostary (2011) took twelve samples and performed comprehensive leachability testing for PG sampled from one stack in Florida (see Appendix 3). In this study, there were no exceedances of EPA's primary drinking water standards in synthetic precipitation leaching procedure (SPLP) testing and no exceedances of Resource Conservation and Recovery Act (RCRA) toxicity characteristic leaching procedure (TCLP) limits (see Appendix 3). The TCLP and the SPLP tests extracted relatively similar metal concentrations (except calcium).

Another apt risk comparison for the metals in PG are the federal and Florida land application limits for biosolids[115] (see Appendix 3). EPA limits were based on a risk assessment for 14 exposure pathways, including groundwater (Table 6 in U.S. EPA 1995 for a guide on the Part 503 Rule.).[116] For metals in biosolids, EPA found that leaching into groundwater or runoff into surface waters were <u>not</u> limiting pathways (see Appendix 3).

For the purposes of an EPA NESHAP review, it is important to understand and consider the fact that groundwater protection is primarily governed by state law and is considered under federal and state highway guidance. For example, the Florida Department of Transportation's Standard Specifications For Road And Bridge Construction states roads must: (a) "[p]rovide erosion control measures where work is accomplished in conjunction with the project, to prevent erosion, pollution of water, detrimental effects to public or private property adjacent to the project right-of-way and damage to work on the project;" (b) "[d]o not drive in, operate, or place construction equipment or materials in surface waters, wetlands, groundwater, or property beyond the project limits without permitted authority for permanent or temporary impacts; and (c) [d]o not allow water that does not meet state water quality standards or does not meet the permitted criteria to exit the project limits.[117] That is, metals impact on groundwater will and should be determined at the local level.

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[114] Appendix 3.

[115] 40 C.F.R. Part 503. Fla. Admin. Code 62-640.

[116] EPA, A Guide to the Biosolids Risk Assessments for the EPA Part 503 Rule, EPA/832-B-93-005 (1995), *available at* https://www.epa.gov/sites/production/files/2018-11/documents/guide-biosolids-risk-assessments-part503.pdf.

[117] Florida Spec Book, *supra* note 23, at 131.

The fact that materials utilized to construct roads can impact the environment has been reported by the NAS,[118] states,[119] and other federal agencies,[120] and applies to all road construction material, not just PG. States provide comprehensive guidance on roadway design.[121] Thus, regardless of the source of the road construction material, the federal, state, and local road building agencies will assess the environmental and physical characterization to determine whether there is an impact from utilizing material A versus material B and decisions on how to mitigate any impacts is within the discretion of these agencies.

Lastly, the footprint of a road on the landscape is very small compared to agricultural lands upon which biosolids and amendments with many higher allowable metal concentrations than those in PG are permitted for continuous use (see EPA 1992 BID). The smaller footprint and lower likelihood of leaching from a constructed road compared to an agricultural field indicates that the influence on groundwater from PG in the road is likely to be comparatively very small. The amount of PG in road base is expected to be negligible in comparison and thus can be used safely in road construction given the lower metals content in PG and the smaller footprint and confinement of the base layer above the water table.

In summary, the presence of other substances that are not radionuclides in PG is unlikely to present an unacceptable worker exposure or adversely impact groundwater or surface water quality. The leaching pathway is likely not a complete pathway of concern for the PG use in road construction proposed in this Petition.

F. Risks From Other Pathways

The Response to EPA Comments on January 16, 2020 (Appendix 4a) contains an explanation of the low risks from other pathways (air, ingestion of food from a garden, etc.) and the rationale for not duplicating the risk assessment on these pathways from the 1992 BID risk assessment.

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[118] The National Academies of Science, Assessing and Managing the Ecological Impacts of Paved Roads (2005), *available at* https://www.nap.edu/catalog/11535/assessing-and-managing-the-ecological-impacts-of-paved-roads.

[119] Idaho Transportation Department, Impacts of Using Salt and Salt Brine for Roadway Deicing, RP 231 (2014), *available at* https://www.ctcandassociates.com/work-samples/saltimpacts.pdf.

[120] USDA, Reclaimed Materials and Their Application in Road Construction: A Condensed Guide for Road Managers (December 2013), *available at* https://www.fs.fed.us/t-d/pubs/pdfpubs/pdf12771807/pdf12771807dpi72.pdf.

European countries compile information on mitigation environmental impacts. Roadex Network, Environmental Issues on Low Volume Roads, *available at* https://www.roadex.org/e-learning/lessons/environmental-considerations-for-low-volume-roads/preface-environmental/.

[121] Florida Department of Transportation, Manual of Uniform Minimum Standards for Design, Construction and Maintenance for Streets and Highways (Draft), Chapter 4 (2018), *available at* https://www.fdot.gov/roadway/floridagreenbook/fgb.shtm (Commonly known as the Florida Greenbook).

G. Comparison of TFI Risk Assessment and Screening Evaluation with EPA's 1992 EPA Background Information Document (BID) Risk Assessment

Appendix 2 performed a very "high level" and preliminary overview of the main differences that we could readily identify between the dose and risk results provided in EPA's 1992 BID and those previously discussed in this report. The following is a list of comparisons:

- A 1:1 dilution of PG with soils (higher PG to soil than EPA's 1:2 PG to soil in 1992. Appendix 2, 1992 BID page 4-9).

- A road thickness of 0.25 m (the same as in 1992).

- The current risk assessment considers the same receptors as EPA did in 1992 as well as two additional receptors suggested by the EPA, namely, the truck driver transporting PG to the construction site and a utility worker who works some time in a trench cutting across a road constructed with PG.

- For the road construction worker, the EPA considered workers standing on the road base and unshielded, as was also assumed for the current risk assessment.

- The current risk assessment assumes a worker moves around over the road surface and is exposed at the average of the gamma fields at the center and edge of the road. While not fully clear, the EPA in 1992 may have assumed a worker was always in the center of the road which would largely account for the difference between gamma doses estimated in 1992 and now.

- The road user is assumed in both cases to drive on a road with a PG base and a cover (in 1992 asphalt or cement) and in the present analysis, for purpose of illustration, concrete road surface was assumed. Only annual dose and risk are available from the 1992 risk assessment. The 1992 EPA risk assessment used a 0.6 shielding for the road user, but rather than determine the degree to which vehicles have changed in the amount of metal in the under carriage of cars, the current risk assessment takes no credit for shielding provided by the vehicle that would provide some level of shielding which is a conservative assumption and could reasonably be considered.

- The dose to the nearby resident is dominated by exposure to gamma radiation which decreases rapidly with increasing distance from the edge of the road. The 1992 risk assessment assumed the nearest resident would be at 100 meters (approximately 328 ft) from the edge of the road. The current assessment considers the RME exposure scenario to be a resident whose home is located a distance of 50 feet from the edge of the road (an urban resident whose home is at 20 feet from the edge of the road is also calculated to illustrated the change in exposure levels with distance).

- The 1992 BID mentions the presence of metals, but did not consider any substances other than radionculides in the 1992 risk assessment. The current Petition includes a metals screening evaluation to justify the fact that a quantitative risk assessment is not warranted.

- The EPA BID risk assessments considered a reclaimer scenario with exposures from gamma radiation and radon, in which the surface is removed and a house is directly built upon PG, and a resident lives in the house for 70 years (see Petition's Risk Assessment and Appendix 4b for a full review of the so called reclaimer scenario).

    - At EPA's request, this Risk Assessment calculated this reclaimer scenario, even though such a scenario is an extreme hypothetical case that is not a RME exposure. Both the 1992 and present calculation assume the surface is removed, but the current assessment takes into account the necessary construction site preparation and grading, which reduces the thickness and to a lesser degree, the concentration of residual road base construction activity that would be necessary to construct a house.

    - The 1992 BID does not indicate how the risk from radon was calculated (dose from radon was not reported in the 1992 BID).

    - The 1992 BID assumed 70-years residency and the current assessment uses EPA's current RME for duration living in a residence of 26-year residency (the upper 90th percentile) (see more in depth discussion in Sections I(B), III(A)(2), and IV (D)(9), above). Even the 1992 BID risk assessment used 26 years as the duration a person might reside in the house. Thus, the 70-year residency for the reclaimer scenario in the 1992 BID appears to be inconsistent with the residency lengths used by EPA in other parts of the 1992 as well as current EPA guidance.

    - The current assessment also assumes a 6 ml poly layer which is standard as a vapor barrier in current home construction.

    - Both the 1992 BID Risk Assessment (at Table 4) and the Petition's Risk Assessment calculated the risk based on an assumed concentration of radium (226) (26 pCi versus 27 pCi/g).[122]

These comparisons demonstrate the upper bound nature of the risk assessment. Actual doses and risks are likely to be lower.

V. RISK MANAGEMENT DECISION

TFI has provided information required by EPA[123] necessary for completing the agency's evauation and determination that use of PG in road construction may be deemed at least as protective of human health as disposal on a stack. Risk management factors favor approving the use of PG for road construction. The petition and supporting risk analysis demonstrates that this use can be advanced safely. Justifications for this determination include:

The Risk Management limit of 3 in 10,000 is consistent with other NESHAP risk limits.

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[122] The 1992 BID Risk Assessment include in the table the risk from a range of radium (226) concentrations.

[123] Information requirements at 40 C.F.R. §§ 61.206(b) (1), (2), (6), (7), (8), and (9) for EPA approval based on a risk assessment determination and conditioned upon receipt of information requirement (3), (4), (5), and (10).

- The highest Reasonably Maximum Exposure (RME) for the use of PG in road construction, 0.5 in 10,000 (0.5 in 10,000 is 5 in 100,000), is well below the NESHAP radionuclide risk management limit of 3 in 10,000.

- For ease of calculation, this Risk Assessment used a nominal average radioactivity level in PG of 27 pCi/g. By "nominal average" we mean this is the average radioactivity level we used in our initial calculation. This number is reasonable and is similar to numbers EPA previously used.

- Once the risk from the initial calculation is determined, EPA can then estimate the risk from higher and lower radioactivity levels. For example, if the average radioactivity level for a stack is (13.5 pCi/g, then the risk is one half of that calculated for 27 pCi/g).

- At EPA's request, TFI members recently sampled PG from multiple gypstacks (Appendix 5). This report confirms that the existing data supports the use of the PG stacks in the U.S for use in road construction. In summary, the average radioactivity level for each stack was significantly lower than 27 pCi/g.

- Furthermore, the risk assessment performed for this Petition demonstrates that 27 pCi/g corresponds to a cancer risk of 0.5 in 10,000 for the highest RME use of PG in road construction (i.e., the road construction worker), therefore the risk from these stacks is less than 0.5 in 10,000. Based on the risk assessment performed for this Petition, EPA's PG risk management safe risk level of 3 in 10,000 corresponds to a radium (226) concentration in the PG of 148 pCi/g (see Sections I(B) and III(B)(3) and Appendix 2). Thus, PG materials in TFI's member's stacks may be safely used as road construction material. It is extremely unlikely if not impossible for random variation in the PG radioactivity levels to exceed an average 148 pCi/g, the radioactivity level that corresponds to a 3 in 10,000 risk management level. EPA performed extensive modeling of the likely migration of radionuclides from PG used in road construction in a 1992 assessment discussed below. The EPA concluded that the radionuclide doses from the groundwater pathways are all negligible. EPA's assessment demonstrates that the radionuclide risks were found to be zero.

- Screening evaluation of the potential impact of metals in PG shows that PG can be used safely by workers in road construction. Paving limits direct contact by the community and also limits water contact with PG isolated in the base layer.

- Care has been taken in the assessment process to manage scientific uncertainties by choosing values and approaches that are likely to overestimate rather than underestimate risks. These result in an RME value, which serves as a reasonable upper bound on the risk distribution and is a readily accepted approach for representing maximum exposures (see Appendix 2). It also provides insight into risks to the population. RMEs overestimate risks for highest exposure situations such that actual risks would be lower.

- For perspective on exposure magnitudes, radiation levels from the use of PG are compared to naturally occurring background. Each exposure scenario has incremental radiological dose that are well below naturally occurring background levels. Exposures

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to the public using the road or living immediately adjacent to the road are likely to be indistinguishable from the natural variability in background.

- There are naturally occurring background radiation and metals in other non-PG construction material including coal ash, fly ash, bottom ash, and other common construction materials. These materials have been deemed safe to use in road construction and other applications. Similarly, this Petition demonstrates the same is true for PG. The use of PG for road construction is consistent with EPA policy on recycling of wastes and waste residuals.The use of PG for roadway construction provides a net economic benefit.

- Approval of the use of PG for road construction is consistent with the Administration's regulatory reform policies.

A. Overview

The regulatory decision to approve a new use for PG is a risk management decision that is assigned to the Assistant Administrator for Air and Radiation. Risk management decisions involve weighing the results of a risk assessment with "the results of other technical analyses and nonscientific factors, to reach a decision about the need for and extent of risk reduction to be sought in particular circumstances and of the means for achieving and maintaining that reduction."[124]

This Petition and its Appendices provide the facts and science required to approve this Petition. This subsection applies these facts and the science to EPA's risk management factors and explains TFI's position that approval is appropriate.

B. The Risk Management Level of 3 in 10,000 is Consistent with Other NESHAP Goals

The EPA Office of Air and Radiation policy is to make a case-by-case decision concerning the acceptability of the risk from exposure to radionuclides.[125] However, the PG risk management limit of 3 in 10,000 is consistent with other typical EPA risk management decisions.

C. The Highest RME Risk Scenario for the Use of PG in Road Construction is Below the NESHAP Radionuclide Risk Management Goal of 3 in 10,000

This Petition demonstrates that the risks of using PG material in constructing roads satisfy the risk management goal for approved alternative uses of PG. In fact, the risk of PG in road construction is well below the risk management goal of 3 in 10,000.

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[124] Institute of Medicine, Environmental Decisions in the Face of Uncertainty, Box 2-1 (2013), *available at* https://www.ncbi.nlm.nih.gov/books/NBK200844/box/box_2_1/?report=objectonly (Uncertainty in Environmental Decisionmaking).

[125] 1989 Rule, *supra* note 3, at 51,564.

The risks from all exposure scenarios were calculated, but the highest RME risk is calculated for the road construction worker who is involved with paving the road with PG that is mixed with soil (i.e., a cancer risk of 0.5 in 10,000, lower than the PG alternative use risk management goal of 3 in 10,000). EPA has long concluded that 3 in 10,000 is the equivalent of the risk from the existing PG stacks, so this alternative does not present a meaningful difference in the risk from the existing stacks. The focus is on the road construction worker since the risks from all other exposure scenarios fall below 110 mrem during road construction use and are of lower risk, although the road worker's risk falls within EPA exposure limits as well.

The vast majority of road construction workers have much lower risks than those calculated in this Petition. Highway construction workers not directly working on the road are located further from the PG and the associated risks are lower.

The risk calculation for the highest RME for a worker placing road base assumes that the PG emits 27 pCi/g exposure for five years. Based on the preliminary data on radiation levels from PG stacks, the average level of radioactivity from the PG material in each sampled stack is less than the nominal 27 pCi/g used in the risk assessment, thus, the risk from these sampled stacks is even further below the EPA risk management safe limit of 3 in 10,000 risk level. The calculated risk is scalable, i.e., if the radioactivity level in a stack is 13.5 pCi/g, the risk is one half of the risk calculated for the nominal radioactivity level of 27 pCi/g (i.e., the 13.5 pCi/g stack corresponds to a 0.28 in 10,000 risk level, significantly lower than the EPA PG risk limit of 3 in 10,000). On average, the RME exposure and the dose to risk conversion for road construction workers using PG are likely to overestimate risk.

Similarly, the highest RME to a resident living near a road (the resident lives in a home located 50 feet or more from a road for 26 years) assuming the PG contains 27 pCi/g is approximately a 0.08 in 10,000 cancer risk, again, well below the PG use risk management goal of 3 in 10,000. Most residents living near roadways are located further than 50 feet from the edge of the road, and the RME exposure and dose to risk conversion are likely to overestimate risk.

The reclaimer scenario is not a RME since it is such a rare potential event, and should not be used in the risk management decision. Nonetheless, the risk assessment report calculated a risk using RME-type exposure input below the PG use risk management goal of 3 in 10,000.

D. Science Policy Assumptions and Uncertainties are Taken into Account in the Final Risk Management Decision

1. Overview

Each of the factors EPA considers in its risk management decision has sensitivities, variabilities, and uncertainties. EPA specifically considered uncertainties and other nonrisk factors in its 1989 and 1992 decisions on acceptable alternative uses of PG.[126]

A recent NAS report recommended incorporating an uncertainty analysis, which was broadly defined to include sensitivities, variability, and various other uncertainties, into EPA

[126] EPA PG Workbook *supra* note 43, at 5.

decisions.[127] This NAS report recommends that an "uncertainty analysis" be "designed on a case-by-case basis."[128] EPA considered uncertainties in previous risk calculations and decisions concerning alternative uses of PG.[129] However, combining RME with the inherent uncertainties in the dose to risk conversion factors can yield risks that are overly conservative compared to actual risks.

Science policy influences both the exposure calculation and the cancer potency and noncancer risk factors that convert the exposure to risk. The EPA decision makers and the public need to understand how policy influences the risk calculation. Put simply, regulatory risk is not the same as actual harm. Unduly conservative risk calculations do not serve the public, since they divert limited resources to issues that present less risk. Science policy based on accumulations of conservative assumptions, including extra layers based on uncertainties, can distort risk estimates and undermine the value and credibility of risk management decisions.

2. Measurement Variation and Uncertainty

Each calculated risk depends upon how sensitive the calculation is to changes in the measurements and input values used in any risk assessment. Risk is assumed to be linearly proportional to dose and the length of exposure. For example, if the concentration of radionuclide in PG increases by 10%, the dose (and, therefore, the risk) increases by 10%. Similarly, if the length of exposure increases by 20%, the total dose increases by 20%. See Section IV, above for a discussion of the variation.

3. Variation by Location

Some of the inputs to risk assessments naturally vary. For example, the average radioactivity level in PG stacks depends upon the source of the phosphate ore and other site specific factors. This risk assessment assumed average radioactivity levels of 27 pCi/g. However, the average level of radioactivity in PG stacks in the TFI 2019 sampling varied from 6.3 to 27.9 pCi/g and data from 1988 had average stack concentration of 34 pCi/g (see Sections I(B), III(B)(3), and Appendix 5). Even levels of 148 pCi/g are safe.[130] Again, dose is directly proportional to the radioactivity level.

4. Variation Due To Design Facts

The Risk Assessment was developed to examine a conceptual road design, to provide an estimate of the upper end RME risks associated with PG use in roads. This approach is appropriate because it is impractical to perform a risk assessment that uses different values for every conceivable road design. Neither the 1989 nor the 1992 BID risk assessment considered every conceivable road design.

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[127] Uncertainty in Environmental Decisionmaking, *supra* note 124, at 5.

[128] *Id.*

[129] EPA PG Workbook, *supra* note 43, at 5.

[130] Based on the risk assessment, PG with radiation levels a couple of times greater than 27 pCi/g may still be utilized for road construction. In fact, an average radiation level of 148 pCi/g corresponds to EPA's risk management goal of 3 in 10,000.

The following factors utilized to minimize the impact of any uncertainties are discussed in the Response to EPA Comments on January 16, 2020 (Appendix 4a).

- The 2019 radiological testing demonstrates that no individual radium (226) concentration the exceeds 35 pCi/g radium (226) concentration requested as a concentration limit and the measured stack averages are well below the 3 in 10,000 safe risk level (i.e., a radium (226) concentration of 148 pCi/g).

- The EPA 1992 BID assumed a 1:2 dilution of PG with soils for a road base concentration of 10 pCi/g. The Petition's Risk Assessment utilized less dilution (1:1 PG:soil).

- The EPA 1992 BID assumed the road base was 0.25 m thick and 30 feet (9.15m) wide and that the road base is covered with a 0.12 m (5 in) thickness of asphalt. The Petition's Risk Assessment utilized a road thickness of 0.25 m (the same as in the EPA 1992 BID).

- The EPA 1992 BID assumed PG in a concrete road incorporates 15% PG by weight and 0.12 m thick (5 in) and 24 feet wide (7.32 m). The Petition's Risk Assessment reviewed road base design criteria and concluded 15% was a high-end criterion.

- The EPA 1992 BID used exposure to the critical population group member (nearby resident 100 m (i.e., 328 ft) from the edge of the road). The Petition's Risk Assessment calculated the radiation levels at 50 feet from the edge of the road.

- The current risk assessment assumes a worker moves around over the road surface and is exposed at the average of the gamma fields at the center and edge of the road, which is more reasonable than assuming a worker never moves for 5 years. The stationary worker is not realistic or reasonable, therefore it is not an RME.

- The 1992 EPA risk assessment used a 0.6 shielding for the road user, but rather than determine the degree to which vehicles have changed the amount of metal in the under carriage of cars, the current risk assessment takes no credit for shielding provided by the vehicle which would provide some level of shielding which is a conservative assumption and could reasonably be considered.

- The current risk assessment considered two receptors beyond those considered in the 1992 BID (truck driver and utility worker).

5. <u>The Influence of Exposure Policies</u>

It is well settled that exposure is not sufficient to support regulation unless there is a significant risk.[131] Because empirical data are often not available, a 2013 National Academies of Science

[131] "When the administrative record reveals only scant or minimal risk of material health impairment, responsible administration calls for avoidance of extravagant, comprehensive regulation. Perfect safety is a chimera; regulation must not strangle human activity in the search for the impossible. *Indus. Union Dep't. v. API*, 448 U.S. 607, 642 (1980). *See Natural Resources Defense Council v. EPA*, 824 F.2d at 1164-65.

(NAS) report noted that EPA's risk assessment policies and practices rely heavily on default options or generic approaches.[132] These approaches can introduce high levels of uncertainty into risk assessments.

As noted above, the "intent of the RME is to estimate a conservative exposure case (i.e., well above the average case) that is still within the range of possible exposures."[133] A NAS Committee reviewing EPA's regulation of technologically enhanced naturally occurring radioactive material (TENORM) recommended that EPA "should use exposure and dose risk assessments that are 'reasonably realistic'" in developing standards for exposure to the various types of low level naturally occurring radiation.[134] The Committee defined "reasonably realistic" as "not....intended to greatly overestimate or underestimate actual effects for the exposure situation of concern" and EPA agreed with the Committee's recommendations.[135] Thus, by definition, RME exposures should be intentionally set at levels that are at the high end, but not an extreme worst case.

The use of defaults has been criticized by independent commentators for: (a) "lack of an adequate scientific basis;" (b) the fact that default "can mask the uncertainty;" (c) observations that defaults can be "overly conservative;" (d) the fact that cumulative impact of uncertainties is not well defined; and (e) concerns "whether there is any basis for believing that the upper-bound estimate for one substance has the same relation to the 'true' risk as it does for another substance."[136]

The Response to EPA Comments on January 16, 2020 (Appendix 4a) summarizes and expands on the discussion of the reasons that the RMEs are supportable and consistent with EPA policies and the recommendations of learned advisory bodies.

6. Risk Factor Policies and Uncertainties

EPA has long utilized (and courts have long upheld) the principle that a 1 in 10,000 risk level is "safe." As a unanimous *en banc* ruling of the Court of Appeals for the District of Columbia Circuit candidly noted, the basis for claiming harm from exposure to chemicals at extremely low environmental levels is more a function of "the rules of arithmetic rather than because of any knowledge" and there was "no particular reason to think that the actual line of the incidence of

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[132] *See* Uncertainty in Environmental Decisions, *supra* note 124, at 58. *See also* National Research Council, Science and Judgment in Risk Assessment, 65 (1994), *available at* http://www.nap.edu/openbook.php?record_id=2125&page=65. *See also* General Accounting Office, Use of Precautionary Assumptions in Health Risk Assessments and Benefits Estimates, GAO-01-55, 7 (October 2000), *available at* https://www.gao.gov/products/GAO-01-55.

[133] EPA Risk Assessment Guidance for Superfund, *supra* note 10, at 7-1.

[134] EPA Report to Congress Re: TENORM, *supra* note 75, at 15.

[135] *Id.* citing the NAS Report at p. 245. "If high-end values are chosen for every exposure factor, then the resulting exposure estimate may no longer be consistent with the RME and may exceed the realm of possibility altogether." ITRC, Decision Making at Contaminated Sites, *supra* note 10, at 6.1.1.

[136] Uncertainty in Environmental Decisions, *supra* note 124, at 58. The RME and other factors utilized in the risk assessment are documented in the literature (*see* RESRAD documentation, EPA guidance or as justified in the various Appendices to this Petition).

harm is represented" by the assumption selected by EPA.[137] This acknowledgment is also apt for the risks from radionuclides.

The 2013 NAS noted that:

> EPA originally selected the linear, no-threshold default as a "conservative" or "health-protective" policy choice because it assumes that there is no dose below which risks are not increased. It is likely to generate the highest, or upper-bound, risk estimate consistent with the data; the actual risk almost certainly will not exceed the upper bound and will likely fall below it.[138]

Use of the International Commission on Radiological Protection (ICRP) value (proposed by the international institution whose purpose is to provide such advice) is supported by several factors:

First, ICRP is an expert advisory body that offers its recommendations to regulatory and advisory agencies, mainly by providing guidance on the fundamental principles on which appropriate radiological protection is based. The 2007 recommendation was produced "after eight years of discussions, involving scientists, regulators, and users all around the world."[139]

Second, the Petition's use of the ICRP dose to risk conversion factor is consistent with EPA's radiation risk assessment factors and procedures. For example, the EPA 2011 radiation guidance[140] provides cancer risk factors for uniform whole-body exposures of low-dose gamma radiation to the entire population, essentially the same dose to risk conversion range derived by the ICRP.

Similarly, as noted above, the organization chartered by the U.S. Congress in 1964 to, among other things, "develop … recommendations about …protection against radiation" (i.e., the United States National Council on Radiation Protection and Measurements (NCRP)) uses the same dose to risk conversion factor as the 2007 ICRP.[141]

Third, the international scientific and regulatory communities have widely adopted the ICRP recommendations.[142]

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[137] *Natural Resources Defense Council v. EPA*, 824 F.2d at 1165.

[138] Uncertainty in Environmental Decisions, *supra* note 124, at 58.

[139] 2007 ICRP Recommendations, *supra* note 88, at 3.

[140] EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population, *supra* note 92.

[141] Management of Exposure to Ionizing Radiation, *supra* note 93, at 42.

[142] *See* Radiation Protection and Management of NORM Residues, *supra* note 59, at 165. The IAEA was founded to "establish or adopt … standards of safety for protection of health and minimization of danger to life and property" and while "[r]egulating safety is a national responsibility . . . many States have decided to adopt the IAEA's standards for use in their national regulations" (including Sweden, Denmark, the Netherlands, the UK, Japan, Canada, Belgium, Japan, and the EU). IAEA, Governmental, Legal and Regulatory Framework for Safety, 7 (2016), *available at* https://www.iaea.org/publications/10883/governmental-legal-and-regulatory-framework-for-safety.

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Fourth, the International Atomic Energy Agency (IAEA) (an organization in which the U.S. is a member and helped establish) and the European Union (as well as each of its member countries) utilized a 1 millisievert (1 mSv) per year acceptable level of radiation exposure, which has been widely adopted by the international community, such as the IAEA and EU regulations. This corresponds to a 26-year total dose of 26 mSv (i.e., 2,600 mrem).

The ICRP approach is more stringent than the large, and growing, body of scientific literature that radiation risks have a threshold. Also, in 2015, a U.S. Nuclear Regulatory Commission (NRC) Advisory Committee acknowledged that:

> There is a large, and growing, body of scientific literature as well as mechanistic considerations which suggest that 1) the LNT model may overstate the carcinogenic risk of radiation at diagnostic medical, occupational, and environmental doses and 2) such low doses may, in fact, exert a hormetic (i.e., a beneficial or protective) effect.[143]

The United Nations Scientific Committee on the Effects of Atomic Radiation notes that below doses of 100 to 200 mGy (roughly equivalent to 10,000 to 20,000 mrem), "[e]pidemiological studies alone are unlikely to be able to identify significant elevations in risk."[144]

Because, as a matter of policy, neither EPA nor the Nuclear Regulatory Commission has changed its "no threshold" default assumptions, this Petition does not seek to go beyond the widely accepted ICRP value. In reality, the actual risk may be lower.

E. Comparison of Radioactivity Levels from Use of PG and Naturally Occurring Background

Each exposure scenario we assessed results in a radiation dose well below the annual natural background level (see Table 1, above). The annual background level of naturally occurring radiation is 310 mrem.[145] For a 26 year period, the cumulative dose is 8,060 (310 mrem times 26), thus the total dose for a nearby resident (16 mrem) given this PG use is 0.2% of the cumulative natural background dose levels ((16 divided by 8,060) (See Section I(B) and Tables 4 and 5, above)). For the RME construction worker scenario (a risk of 0.5 in 10,000), the RME worker dose is 7% of the background dose for a worker at a road construction site not using PG. (see Tables 4 and 5, above summarizing the risks from all exposure scenarios). As a result, there

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See Council Directive 2013/59/Euratom, *supra* note 95.

See UNSCEAR, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, 8 and n. 17 (2010), *available at* https://www.unscear.org/docs/reports/2010/UNSCEAR_2010_Report_M.pdf (UNSCEAR Report).

[143] Nuclear Regulatory Commission, Advisory Committee on the Medical Uses of Isotopes (ACMUI), Report on the Hormesis/Linear No-Threshold Petitions, 1 (October 14, 2015), *available at* https://www.nrc.gov/docs/ML1528/ML15287A494.pdf.

[144] UNSCEAR Report, *supra* note 142, at 8.

[145] Appendix 2.

will be no meaningful incremental increase above the background exposure dose for any of the exposure scenarios, but particularly for the nearby resident and road user.

Background levels of radiation are often considered in governmental decisions. For example, EPA's PG Workbook compares the risk from use of PG to background levels of radiation.[146] When the calculated risk for receptors in a risk assessment is lower than background, it is a relevant factor in the risk management decision.

F. EPA Policy Supports Recycling of Wastes and Waste Residuals

EPA's 1989[147] and 1992[148] risk management decisions concerning alternative uses of PG took into account the Agency's overarching policy of supporting recycling. Since 1992, EPA has increased its emphasis on adopting sustainability policies.

EPA has prioritized policies to encourage recycling of a wide variety of byproducts and other materials.[149] Similarly, the U.S. Department of Agriculture also has issued guidance on using various reclaimed materials in road construction.[150] The recycling of PG decreases raw material costs for companies and government entities that use the PG material. It also decreases greenfield impacts, increases beneficial land use, and reduces long-term maintenance costs. Reuse of PG avoids potential environmental concerns with long-term storage of PG. As EPA notes in the context of coal ash use:

> Beneficial use is the recycling or use of coal ash in lieu of disposal. For example, coal ash is an important ingredient in the manufacture of concrete and wallboard, and EPA supports the responsible use of coal ash in this manner. This final rule supports the responsible recycling of coal ash by distinguishing beneficial use from disposal.[151]

EPA recently concluded that:

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[146] EPA PG Workbook, *supra* note 43, at 13 ("To put this number in perspective and to illustrate how little additional risk is permitted, the risk in the United States of developing a fatal cancer (from all causes) is about one in four").

[147] 1989 Rule, *supra* note 3.

[148] 1992 Rule, *supra* note 48, at 23,306.

[149] "Sustainable Materials Management (SMM) refers to the use and reuse of materials in the most productive and sustainable way across their entire life cycle. On a broader scale, SMM looks at social, environmental and economic factors to get a more holistic view of the entire system. The benefits of maximizing this connection include conserving resources, reducing waste, slowing climate change, and minimizing the environmental impacts of the materials we use." EPA, Advancing Sustainable Materials Management: 2016 Recycling Economic Information (REI) Report, EPA 530-R-17-002, 2 (2016), *available at* https://www.epa.gov/sites/production/files/2017-05/documents/final_2016_rei_report.pdf.

[150] Reclaimed Materials and Their Applications in Road Construction, *supra* note 120.

[151] EPA, Frequent Questions about Beneficial Use of Coal Combustion residuals (CCR) (last updated March 26, 2019), *available at* https://www.epa.gov/coalash/frequent-questions-about-beneficial-use-coal-ash.

> [E]nvironmental releases of COPCs from CCR fly ash concrete and FGD gypsum wallboard during use by the consumer are comparable to or lower than those from analogous non-CCR products, or are at or below relevant regulatory and health-based benchmarks for human and ecological receptors. Thus, EPA supports the continued beneficial use of coal fly ash in concrete and FGD gypsum in wallboard. Furthermore, the Agency believes that these beneficial uses provide significant environmental and economic benefits, and opportunities to advance Sustainable Materials Management (SMM).[152]

The use of CCR for beneficial use in road construction is analogous to and supports the Office of Air and Radiation's approval of the use of PG in road construction. More generally, approval of the use of PG in road construction is consistent with EPA's policy of encouraging recycling.

G. Naturally Occurring Background Radioactivity and Metals are Present Widely in the Environment, Including Existing Road Construction Materials

Many consumer products contain radioactive components (smoke detectors, clocks and watches, older camera lenses, older gas lantern mantles, older televisions and computer monitors, sun lamps and tanning salons, ceramic materials such as tiles and pottery, glassware, and some EXIT signs, among other products).[153] Most consumer products contain metals. Similarly, "[r]adioactive materials (including uranium, thorium, and radium) exist naturally in soil and rock."[154] Essentially all air contains radon and many types of soil and natural rock emit radiation.[155] In addition, virtually all road construction materials contain radioactivity and metals.

Coal ash, fly ash, bottom ash, natural gypsum, and other common construction materials[156] contain radioactive material (see Table below).[157]

A 2014 evaluation of coal ash beneficial uses concluded that:

> All of the existing evaluations identified concluded that radiation exposures from fly ash concrete are not a major source of concern. Several of these existing evaluations compared fly ash concrete to analogous products and found that the potential exposures

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[152] EPA, Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard, 5-25 (Feb. 2014), *available at* https://www.epa.gov/sites/production/files/2014-12/documents/ccr_bu_eval.pdf (Coal Combustion Residual Beneficial Use Evaluation).

[153] EPA, What kinds of consumer products contain radioactive materials (last updated on September 19, 2019), *available at* https://www.epa.gov/radiation/what-kinds-consumer-products-contain-radioactive-materials.

[154] U.S. Nuclear Regulatory Agency, Natural Background Sources (last updated October 2, 2017), *available at* https://www.nrc.gov/about-nrc/radiation/around-us/sources/nat-bg-sources.html#terr.

[155] *Id.*

[156] See Attachment B: Road construction specification examples.

[157] EPA Report to Congress Re: TENORM, *supra* note 75, at Appendix A.

> do not represent an appreciable addition to the background radiation that the general public is subjected to on an annual basis. Naturally occurring radionuclides are present throughout the environment in food, air, water, soil, consumer products, and even the human body. All natural resources used in building construction (e.g., cement blocks, bricks, granite, soil, rocks) contain some trace level of naturally occurring radionuclides. For example, the USGS concluded that "the radioactivity of typical fly ash is not significantly different from that of more conventional concrete additives or other building materials such as granite and red brick." The NCRP concluded that exposures from living in concrete buildings containing fly ash are "similar to calculations made for individuals living in a brick and masonry home. Consequently, it is assumed that the use of [coal ash] in building materials has not substantially increased the average dose to an individual in the population residing in a building constructed with brick or masonry materials."[158]

The United Kingdom Health Protection Agency "concluded that exposures to '…members of the public from the use of [fly ash] in building materials is negligible.'"[159]

Thus, the appropriate risk management consideration is not whether PG has a low level of radioactivity or metals, but whether the risk is below the EPA PG risk management goal of 3 in 10,000.

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[158] Coal Combustion Residual Beneficial Use Evaluation, *supra* note 152, at 1-7.

[159] *Id.*

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Table 6 (copied (without footnotes) from "Appendix A – Table 1, TENORM Materials and References.")

As a comparison to background levels, radium 226 concentrations in soils of the U.S. are shown at the top of the table.

TENORM Material	Range of Radioactivity Concentrations, Radium 226		
	Low	Average	High
Soils of the United States [1]	0.2	1.1	4.2
Uranium Mining Overburden [2]	3	3.0	low hundreds
Uranium In-Situ Leach Evaporation Pond Solids [3]	300	–	3,000
Phosphate Ore (Florida) [4]	7	17.3-39.5	6.2-53.5
Phosphogypsum [5]		11.7-24.5	36.7
Phosphate Fertilizer [6]		5.7	21
Coal Ash [7] -Bottom Ash	1.6	3.5-4.6	7.7
Fly Ash	2	5.8	9.7
Petroleum (oil and gas)	0.1 pCi/l	–	9000 pCi/l
Produced Water [8]	<0.25 pCi/g	<200 pCi/g	>100,000 pCi/g
Pipe/Tank Scale [9]			
Water Treatment Sludge [10]	1.3 pCi/l	11 pCi/l	11,686 pCi/l
Treatment Plant Filters [11]	–	40,000 pCi/g	–
Rare Earths [12]	5.7	–	3,244
Monazite			
Xenotime			
Bastnasite			
Titanium Ores [13]	3.9	8.0	24.5
Rutile	–	19.7	–
Ilmenite	–	5.7	–
Wastes	–	12	–
Zircon [14]	–	68	–
Wastes	87	–	1300
Aluminum [15] (Bauxite) Ores	4.4	–	7.4
Product	–	0.23	–
Wastes	–	3.9-5.6	–
Copper Wastes [16]	0.7	12	82.6
Geothermal Energy Waste Scales [17]	10	132	254

H. Use of PG For Roadway Construction Provides a Net Economic Benefit and is Consistent with the Administration's Regulatory Reform Policies

A detailed report explaining the various economic benefits to be expected from approval of PG use in road construction accompanies this Petition. The report concludes that use of PG in road

construction is expected to produce cost savings ranging from $37 million to $160 million during the period 2020-2042.[160]

The approval would impose no new substantive regulatory requirements and is consistent with Presidential Executive Orders that encourage: (a) reducing unnecessarily burdensome and costly regulation;[161] (b) maximizing the use of goods, products and materials produced in the U.S.;[162] and (c) encouraging innovative strategies and trade policies.[163]

I. Other Benefits to Eliminating PG Stacks

Construction and maintenance of PG stacks are large engineering projects. There are environmental and actuarial risks presented by any such construction project. The approval of PG for use in road construction will reduce future potential risk by limiting the size of existing and potentially eliminating the need for new PG stacks.

J. Final Agency Action

EPA's determination that use of PG in road construction is deemed approved, consistent with certain criteria that must be met prior to use, constitutes final agency action under the Clean Air Act, 42 U.S.C. 7607 (b)(1), and the Administrative Procedures Act, 5 U.S.C. Section 704.

Under established legal precedents, an agency approval conditioned on specified requirements "mark[s] the consummation of the agency's decision-making process" and determines the "rights and obligations" of relevant parties, with "direct and appreciable legal consequences."[164] The approval process outlined above satisfies these legal prerequisites.

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[160] Interestingly, the lost opportunity costs from not using fly in road construction has been estimated at $4.5 billion. Transportation Development Foundation, The Economic Impacts of Prohibiting Coal Fly Ash Use in Transportation Infrastructure Construction, 5 (Sept. 2011), *available at* https://www.artba.org/wp-content/uploads/2017/06/study2011flyash.pdf. EPA should consider this lost opportunity cost in its risk management decision.

[161] Presidential Executive Order on Reducing Regulation and Controlling Regulatory Costs, Executive Order 13771 (Jan. 31, 2017).

[162] Presidential Executive Order on Buy American and Hire American, Executive Order 13788 (April 18, 2017).

[163] Presidential Executive Order on Establishment of Office of Trade and Manufacturing Policy, Executive Order 13797 (April 29, 2017).

[164] *Bennett v. Spear*, 520 U.S. 154, 178 (1997). *Whitman v Am. Trucking, Ass'n*, 531 U.S. 457, 478 (2001).

SIGNATURE PAGE

I, Andrew (Andy) T. O'Hare, CAE, am Vice President of Public Policy for The Fertilizer Institute[165] (the national trade association for fertilizer companies, including the companies that own and/or operate phosphogypsum stacks). I coordinated the preparation of this Petition and am signing on behalf of all of the TFI members who own or operate PG stacks.

_____

Andrew (Andy) T. O'Hare

Vice President of Public Policy

The Fertilizer Institute

[165] Since multiple companies that own and operate PG stacks are making this request, this Petition was prepared and submitted to EPA by TFI on behalf of its members. A representative of TFI is included on the signature page.

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Appendix 3

Human Health Risk Screening for Metals and Metalloids: Phosphogypsum in Road Construction

Prepared for

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October 11, 2019

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Appendix 3 – Human Health Risk Screening for Metals and Metalloids: Phosphogypsum in Road Construction

Introduction

The Petitioners are pursuing reuse of phosphogypsum (PG) in road construction as an alternative to the current practice of stacking. As part of this request, a radiological risk assessment is required[1] and has been completed to evaluate potential public health impacts and demonstrate that the reuse is as safe as stacking. The radiological risk assessment (provided in Appendix 2) was completed with input and oversight from the U.S. Environmental Protection Agency (EPA) Office of Radiation and Indoor Air (ORIA) to evaluate radiological aspects of PG reuse, which, therefore, are not part of this chemical screening assessment. The radiological risk assessment is comprehensive, including multiple reuse scenarios.

Natural materials in PG contain low levels of radioactivity and contain various metals and metalloids. A chemical risk screening was conducted as described herein to evaluate potential risks of metals/metalloids in PG to supplement the radiological risk assessment. EPA's PG reuse guidance (ECRI 2005) requests information on "other toxic or hazardous constituents of the waste" and analyses to "assure that the proposed use does not cause non-radiological risks to human health and the environment."

The risk screening used the following four-step approach:

1. Develop an appropriately (reasonably) conservative screening scenario
2. Select health-protective and conservative screening levels
3. Screen PG data
4. Evaluate screening results.

Evaluation (step 4) included assessing PG concentrations of metals/metalloids in the context of average soil values within the United States. This risk screening employs

[1] Required to demonstrate compliance with National Emission Standards for Hazardous Air Pollutants (NESHAP); promulgated in 1989.

generic EPA screening levels based on reasonably conservative assumptions to provide a reasonable upper-bound estimate of potential risk, as an initial evaluation of the composition of the PG. The risk screening does not constitute a risk assessment and exceedances of conservative risk screening levels should not be interpreted as unacceptable risks.

An evaluation of the leaching potential of metals/metalloids in PG and a comparison to other road construction materials was completed as part of this assessment. The constructed roadway will be paved, and if PG is mixed into the cement, it will be encapsulated. Given this, potential residential exposure pathways were determined to be incomplete (i.e., no exposure) and so were not included in this risk screening. Studies indicate that for the petitioned PG reuse in road construction, leaching to groundwater (or surface water) is likely not a complete exposure pathway of concern.[2] Paving limits water contact of PG isolated within the base layer placed above the water table.

Risk Screening Scenario

A conceptual site model (CSM) was developed in the radiological risk assessment, which included five exposure scenarios. The risk assessment found that the highest incremental dose and risk identified for the exposure scenarios considered was to the road construction worker. To utilize a conservative approach in the metals screening assessment, the exposure scenario with the highest risk (i.e., the road construction worker) was selected for the risk screening scenario. The construction worker screening scenario considered exposure to PG via three routes including incidental ingestion, dermal contact, and inhalation.

The proposed PG reuse in road construction involves mixing PG with soil and compacting to create road base with placement above the water table and paving with or without PG mixed into concrete cement. There are four basic layers in roadway construction, which are, from bottom to

[2] A complete exposure pathway has four components: 1) a source and mechanism of constituent release to the environment; 2) an environmental transport medium for the released constituent; 3) a point of potential contact with the impacted medium (i.e., the exposure point), and 4) an exposure route at the exposure point. Exposure occurs when released constituents are transported to and contact a receptor. Without exposure, there is no risk.

top: embankment/foundation, subgrade, road base, and paving (i.e., concrete). These layers are illustrated in Figure 1 at the end of this memo. The specific use of PG for road construction is within the road base and/or pavement. PG is mixed in the road base (at or less than 50%) with soil or other materials such as sand and aggregates. Road base is a supporting layer of compacted material approximately 0.25 m in thickness[3] beneath the pavement and above the subgrade. It serves to provide resiliency to the road. PG may also be used in a smaller fraction (approximately 2.25%) in the paving. The surface paving serves to isolate the compacted base layer from the environment. This eliminates direct contact with the road base material once the road is paved and limits water contact of PG within the base layer.

Leaching to groundwater (or surface water) is likely not a complete exposure pathway for the petitioned PG reuse in road construction. This is because roadways are sloped to drain precipitation and paving will act as a barrier to infiltration through the compacted road base beneath. Despite this, literature regarding leaching and water quality was evaluated as part of this screening assessment (see the section titled "Leaching and Water Quality").

PG Composition Dataset

A comprehensive literature review was conducted to develop an understanding of the non-radiological composition of PG. PG concentration data were assembled from four domestic and one international study; concentrations from these studies are compiled in Table 1 at the end of this memo.

Florida

The U.S. Bureau of Mines studies published by May and Sweeney in 1984 were conducted to characterize PG under "a variety of conditions encountered in either processing or storage" (May and Sweeney 1984a,b). Nine stockpiles (i.e., stacks) were sampled in Florida from PG generated by two different manufacturing processes; six stacks were active and three were inactive. This published dataset provides average concentrations of trace metals measured in the stacks.

[3] This thickness was selected for the risk analysis.

Calculated average concentrations for at least one part of the study (May and Sweeney 1984a) excluded non-detects, which results in averages that are biased high.

The Mostary (2011) study from University of Florida characterized PG from a stack in Mulberry, Florida. The published dataset provides multiple analyses, including total metals results for samples collected from the top of one stack at four walls.

Idaho

The Luther et al. (1993) study at University of Alberta characterized PG from a decommissioned plant in Southern Alberta that used beneficiated ore from southeastern Idaho. The published dataset presents maximum concentrations of trace metals measured in PG originating from Idaho phosphate rock.

Louisiana

The Taha et al. (1992) South Dakota State University and Louisiana State University study was a joint research program for evaluating PG use as a road base and included two engineering companies. The published dataset is a range of trace metals concentrations measured in Louisiana PG.

International

International PG data were collected and published by the International Atomic Energy Agency (IAEA) in 2013 (IAEA 2013). The IAEA published a dataset of reported minimum and maximum concentrations of trace metals in PG generated in the United States and worldwide.

EPA Screening Levels

The road construction worker scenario was evaluated for incidental ingestion, dermal contact and dust inhalation of PG using EPA's generic Regional Screening Levels (RSLs)[4] published for "composite worker" exposure to soil, which is defined by EPA as follows:

> *This is a long-term receptor exposed during the work day who is a full-time employee working on-site and spends most of the workday conducting maintenance activities outdoors. The activities for this receptor (e.g., moderate digging, landscaping) typically involve on-site exposure to surface soils. The composite worker is expected to have an elevated soil ingestion rate (100 mg per day) and is assumed to be exposed to contaminants via the following pathways: incidental ingestion of soil, dermal contact with soil, inhalation of volatiles and fugitive dust. The composite worker combines the most protective exposure assumptions of the outdoor and indoor workers. The only difference between the outdoor worker and the composite worker is that the composite worker uses the more protective exposure frequency of 250 days/year from the indoor worker scenario* (U.S. EPA 2019).

EPA's generic composite worker RSLs based on either a hazard quotient of 1 for non-cancer effects or a lifetime cancer risk of 1×10^{-6} to address cancer were used as a starting point to perform the human health screening assessment. Non-cancer-based screening levels were used as published by EPA. A simple adjustment was made to the carcinogenic screening levels. The cancer-based RSLs were adjusted from a lifetime cancer risk of 1×10^{-6} to 1×10^{-4} to be in the same range as EPA's cancer risk management level for PG use while maintaining the conservative nature of the exposure assumptions used to develop the screening levels. The lowest RSL (i.e., cancer or non-cancer-based) was selected for metals with cancer and non-cancer effects. The exposure parameter assumptions used by EPA to develop the generic composite worker RSLs are conservative.

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[4] https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables

All road construction materials, including PG, have varying chemical compositions and are used routinely by construction workers. Exposures may be absent or minimized through normal controls and best management practices (BMPs) such as wetting the construction area to prevent dust formation.

Average Soil Concentrations

The highest concentration of each element found in PG from the literature review was compared against the average surface soil (0–5 cm) concentration in the coterminous United States published by the U.S. Geological Service (USGS; Smith et al. 2013). This methodology is a very conservative screening approach since it compares maximum PG values to average soil values. For the elements boron, neodymium, ytterbium, and zirconium, where no data were available from Smith et al. (2013), average surface soil (up to 20 cm in depth) concentrations were taken from a previous USGS dataset (Shacklette and Boerngen 1984). For some rare earth elements (dysprosium, erbium, europium, gadolinium, lutetium, and samarium) without reported values in either Smith et al. (2013) or Shacklette and Boerngen (1984), the highest average concentration was gathered from a review by Tyler (2004). These average United States soil concentrations are summarized in Table 1. The chemical composition of PG is directly related to the mined phosphate ore used to manufacture phosphoric acid. Therefore, the concentration of many of the metals and metalloids in PG are similar to or below these average United States levels (e.g., aluminum, barium, iron, potassium, magnesium, manganese, lead, zirconium, and others), while some of these background constituents are concentrated in the manufacturing process and are higher in concentration in the PG.

Risk Screening

The highest published metals concentrations in PG for the United States and international studies discussed above were screened against the EPA RSLs for a composite worker. Only two metals, lanthanum (La) and zirconium (Zr), exceeded their risk-based composite worker RSLs in PG from some but not all sources in the literature reviewed. To put these maximum concentrations in perspective, both metals were then screened against average concentrations of these analytes in

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surface soils data published by the USGS (Shacklette and Boerngen 1984). Of these two metals, only La exceeded the USGS average concentration in soil.[5] However, PG will be mixed with other road construction materials. As much as 50% PG will be used in road base, and approximately 2.25% will be used in paving.[6] For these mixtures, the maximum La concentrations in PG used in road base and paving are expected to be less than the conservative EPA composite worker RSLs.

Zr is the twentieth most common element in the Earth's crust (Haxel et al. 2002) and resembles titanium in its physical and chemical properties (Shahid et al. 2013). Across the conterminous United States, Zr is found at an average concentration of 180 mg/kg in surface soils (Shacklette and Boerngen 1984), which is greater than the maximum PG concentration reported in the literature reviewed. More than 140 recognized mineral species contain Zr, but zircon and baddeleyite are the main naturally occurring compounds in soil. Zr is generally regarded as immobile in soil due its low water solubility and ability to form strong complexes with many different soil components (Shahid et al. 2013).

La is one of 15 elements commonly known as rare earth elements, and it belongs to a group of elements known as "lanthanides." It occurs naturally in the earth's crust at a concentration of approximately 39 mg/kg (Tyler 2004) and in surface soils in the United States at a concentration of 26 mg/kg (Smith et al. 2013). Among the rare earth group, La is the most electropositive element and occurs uniformly as a trivalent cation (La^{3+}) in a variety of carbonates, oxides, phosphates, and silicates (Gambogi 2013). La occurs naturally in phosphate rocks (such as the source rock for fertilizer production) through binding with PO_4^{3-} anions to form the mineral rhabdophane. In general, lanthanide salts of chloride, nitrate, and perchlorate are soluble, while the hydroxide, carbonate, phosphate, and fluoride salts are insoluble (U.S. EPA 2018). The solubility of La increases under acidic conditions (Larrañaga et al. 2016). La is added to sensitive

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[5] The RSL for La was based on data from the provisional peer-reviewed threshold values (PPRTV) for soluble La; insoluble salts are expected to have considerably different toxicokinetic characteristics. It is expected that only a small portion of the PG would become soluble under environmental conditions. This makes the comparison between maximum La concentrations in PG and the RSL overly conservative due to the limited La solubility.

[6] Cement would include 15% PG, but when it is mixed to generate the concrete paving the overall proportion of PG in the mixture is reduced to about 2.25%.

surface water bodies, including lakes, as the active component in Phoslock, which is used to remove phosphate. Use of La-containing Phoslock in these sensitive areas has been studied and determined to be of "low toxicity and safe to use in all naturally-occurring environmental conditions at the recommended dosages."[7] Therefore, although La occurs naturally in phosphate rocks, and, therefore, in PG, it is handled routinely in certain products, including application by workers in sensitive areas such as lakes.

Comparison to Other Road Construction Materials

All road construction materials have some level of naturally occurring radioactive materials and metals/metalloids. This includes soils, rock, Portland cement, and reused waste materials such as fly ash. As an example, Table 2 summarizes the maximum concentrations reported in literature for PG assembled for the risk screening compared with reported median concentrations in fly ash and Portland cement. As shown in Table 2, a more comprehensive PG dataset was developed for this Petition compared with fly ash and Portland cement datasets reported to EPA to demonstrate the safety of fly ash reuse in concrete and wallboard in 2014 (U.S. EPA 2014).

Of the metals/metalloids reported in fly ash, approximately half of the median concentrations are higher than the maximum concentrations reported for PG. Aluminum and iron concentrations are approximately 16 times higher in fly ash than in PG, and other constituents such as arsenic, chromium, and manganese are slightly higher in fly ash. Boron, barium, beryllium, lead, and vanadium are between approximately 3 to 7 times higher in fly ash compared with PG. EPA has approved the beneficial reuse of fly ash, and its use as a road construction material is excluded from federal regulation. State agencies have primary responsibility for regulating beneficial reuses. Although concentrations of many metals/metalloids are lower in PG than in fly ash, the petitioned reuse of PG in road construction involves applications above the water table in a compact and/or encapsulated form (i.e., in road base and/or paving).

[7] http://www.phoslock.eu/en/phoslock/about-phoslock/

Leaching and Water Quality

In any situation with metals in soils or sediments, leaching is largely governed by pH and environmental conditions. Metals may leach from PG under certain conditions (e.g., laboratory testing; Taha et al. 1992). Some investigators have studied the leachability of PG. For the most part, these studies show limited leaching. This includes a recent University of Florida study by Mostary (2011) with comprehensive leachability testing for PG sampled from one stack in Florida. In this study, there were no exceedances of EPA's primary drinking water standards in synthetic precipitation leaching procedure (SPLP) testing and no exceedances of Resource Conservation and Recovery Act (RCRA) toxicity characteristic leaching procedure (TCLP) limits.

Leaching is not expected to be a complete pathway of concern for the petitioned use of PG in road construction. The specific use of PG for road construction is as road base when mixed (e.g., at or less than 50%) with other materials such as soil, sand, or aggregate. As shown in Figure 1, road base is a supporting layer of material ~0.25 m in thickness beneath the pavement and above underlying soil and fill. It serves to provide resiliency to the road. PG may also be used in a smaller fraction (~2.25%) as part of the surface pavement. The design of new roads as depicted in Figure 1 affects potential for exposures by creating a degree of isolation of the base layer from the environment. This limits direct contact by the community and limits water contact of PG isolated within the base layer.

The wide-scale use and attention paid to the risks of biosolids for land application provides a point of comparison for the risks of metals in PG and associated leaching. The use of biosolids for land application is regulated under the EPA Part 503 Rule,[8] which has been adopted by states (e.g., Florida Chapter 62-640, F.A.C.). Florida had 95 permitted biosolids application sites in 2016 (FDEP 2016). The guidelines establish application limits for nine metals:[9] arsenic, cadmium, copper, lead, mercury, molybdenum, nickel, selenium, and zinc. EPA selected these

[8] See U.S. EPA 1995 for a guide on the Part 503 Rule.

[9] EPA has amended Part 503 periodically since initial publication, including deletion of numerical standards for chromium to be land-applied (60 FR 5464, October 25, 1995).

metals for risk assessment based on an initial risk screening of all the metals that may be present. EPA then evaluated risks to human health for 14 exposure pathways (Table 6 in U.S. EPA 1995). They identified the limiting pathways (i.e., the pathway resulting in the highest exposure risk; Table 11 in U.S. EPA 1995) and associated allowable metals loadings and concentrations in biosolids (Tables 10 and 16, respectively, in U.S. EPA 1995) for continual land application. Limiting pathways determined by EPA involved direct contact or uptake in plants that are subsequently ingested as would be the case for subsistence farmers. For metals in biosolids, EPA found that leaching into groundwater or runoff into surface waters were not limiting pathways.

As described in the metals screening assessment, direct contact exposure for workers applying PG in road construction is within acceptable risk limits. With the exception of two individual cadmium values reported for international studies, the maximum metals levels in PG in mixtures for road construction are also below those set forth by EPA for biosolid application to be safe for direct contact and plant ingestion by the public. These are not complete pathways for roads, inasmuch as the PG is embedded within the road, preventing direct contact and plant ingestion by the public.

It is important to consider that EPA deemed very high allowable metals (biosolids) loadings (many with unlimited risk-based pollutant loadings) to be safe for continuous application on fields that are watered, infiltrating precipitation through the soil column, and moving into surface and ground waters. Moreover, the footprint of a road on the landscape is very small compared to agricultural lands upon which biosolids and amendments with many higher allowable metal concentrations than those in PG are permitted for continuous use. The smaller footprint and lower likelihood of leaching from a constructed road compared to an agricultural field indicates that the influence on groundwater from PG in the road is likely to be comparatively very small. PG in road base is expected to be negligible in comparison and thus can be used safely in road construction given the lower metals content in PG and the smaller footprint and confinement of the base layer above the water table.

State and Federal Road Construction Requirements

The relevant department of transportation has responsibility to ensure that a state- or federal-funded new road project can be constructed and used in a manner that is judged adequately protective of the environment. State law primarily governs groundwater and surface water protection. Road construction projects also rely on local, state, and federal environmental guidance pertaining to water quality protection.

Agencies promote sustainability and use of recycled materials in road construction. The fact that road construction materials can impact the environment has been reported by the National Academy of Science (NAS; CEIRD 2005), states (Idaho; Casey et al. 2014), and other federal agencies (U.S. Department of Agriculture; Melton and Kestler 2013). This applies to all road construction material, not just PG. States provide comprehensive design of roadways with assessment of potential impacts during and after construction and mitigating measures if warranted, regardless of the source of construction materials. The following manuals and guidance documents illustrate agency considerations in the roadway design process.

U.S. Department of Transportation, Federal Highway Administration

The U.S. Department of Transportation, Federal Highway Administration (FHWA) released guidelines for use of coal fly ash and other materials (e.g., kiln dusts) in asphalt concrete, Portland cement concrete, stabilized base, flowable fill, and embankment or fill (FHWA 2016). When the guidelines were first published in 1997, fly ash had been "successfully used as a mineral admixture in PCC for 60 years," "as a substitute mineral filler in asphalt paving mixtures for many years," and "for several decades as an embankment or structural fill material."

FHWA also issued fly ash guidance documentation specifically for highway engineers (ACAA 2003). This included discussion of design issues and consideration of potential environmental impacts.

- "Design issues. The mechanical behavior and compaction characteristics of fly ash are generally similar to those of silt. For this reason, fly ash also shares

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some of the difficulties that are characteristic of silt such as dusting, erosion and frost susceptibility. These difficulties can be properly addressed during the design of the embankment."

- "Environmental impacts. The trace element concentrations in many fly ashes are similar to those found in naturally occurring soils. Although the leachates of some fly ashes may contain trace element concentrations that exceed drinking water quality standards, this is also true of certain soils. State environmental regulatory agencies can guide you through applicable test procedures and water quality standards. The amount of leachate produced can be controlled by assuring adequate compaction, grading to promote surface runoff, and daily proof-rolling of the finished subgrade to impede infiltration. When construction is finished, a properly seeded soil cover will reduce infiltration. For highway embankments, the pavement may be an effective barrier to infiltration.

California Department of Transportation

The California Department of Transportation (Caltrans) Highway Design Manual (Caltrans 2018) includes discussions on controlling water pollution, testing, and availability of road construction materials and encourages use of recycled materials.

- "Control of Water Pollution. Water pollution related to the construction of highways and to the drainage of completed highways should be limited to the maximum extent practicable. This objective should be considered from the early planning, through the detailed design phase, to the end of construction of each project."
- "Materials and Geotechnical Services. The Materials unit is responsible for conducting laboratory testing, field testing, specialized field inspections, and maintaining the test method procedures for the Department. The GS [Geotechnical Services] unit provides the Districts, Structures, and

Headquarters with expertise and guidance in soil related investigations and groundwater issues"

- "Availability of Materials. The availability of suitable materials such as subbase and base materials, aggregates, binders, and cements for pavements should be considered in the selection of pavement type. The availability of commercially produced mixes and the equipment capabilities of area contractors may also influence the selection of pavement type, particularly on small widening, reconstruction or rehabilitation projects. Suitable materials that are locally available or require less energy to produce and transport to the project site should be used whenever possible."
- "Recycling. The Department encourages and seeks opportunities to utilize recycled materials in construction projects whenever such materials meet the minimum engineering standards and are economically viable. Accordingly, consideration should be given on every project to use materials recycled from existing pavements as well as other recycled materials such as scrap tires. Existing pavements can be recycled for use as subbase and base materials to be surfaced with a flexible structural surface course, or as a partial substitute for aggregate in hot mix asphalt mixes. The decision to use recycled materials should be made based on a thorough evaluation of material properties, performance experience, benefit/cost analysis, and engineering judgment."

Florida Department of Transportation

The Florida Department of Transportation (FDOT) Manual of Uniform Minimum Standards for Design, Construction and Maintenance for Streets and Highways (the Florida Greenbook; FDOT 2018). Chapter 1 of the manual includes a section (C.8) for environmental impact planning to mitigate adverse impacts in the project planning stage.

Illinois Department of Transportation

The Illinois Department of Transportation's (IDOT's) Bureau of Local Roads and Streets Manual (IDOT 2018) includes discussion of considering potential groundwater impacts from highway projects. "In the development of proposed LPA [Local Public Agency] highway projects, potential impacts to groundwater resources consideration should be given to implementing practical measures for avoiding, minimizing, and mitigating adverse project impacts to those resources, see Section 26-22 of the BDE [Bureau of Design and Environment] Manual."

Washington State Department of Transportation

The Washington State Department of Transportation (WSDOT) Use of Recycled Materials in Highway Construction document (WSDOT 1992) detailed findings of a research study on the use of recycled materials in highway construction directed by Senate Bill 5143 that investigated tires, glass, asphalt concrete, fly ash, compost, mixed plastics, and aluminum sign stock. The document discusses strategies to test and monitor use of recycled materials in road construction, product specifications, programs to demonstrate feasibility, and identification of recycled material sources and vendors. It includes evaluation with the Washington State Department of Ecology as needed and highlights "large amounts of fly ash" used in WSDOT's reconstruction of the Lacey V. Murrow Floating Bridge (i.e., concrete floating bridge crossing Lake Washington in Seattle completed in 1993) (Lwin et al. 1995).

Roadway design is comprehensive; agencies governing road construction assess construction materials, potential impacts, and if necessary, mitigating measures. Thus, all construction materials, including but not limited to PG, are addressed by the highway construction process. This decision-making is in the purview of the agencies that govern road construction.

Conclusions

A conservative human health risk screening was conducted as a first step to determine whether further risk evaluation is warranted to assess construction worker exposure to metals in PG used

for road construction. The conservative risk screening demonstrates that metals levels in PG are not expected to pose an unacceptable level of health risks to construction workers using PG in roadway construction. Furthermore, proper construction practices employ BMPs such as wetting surfaces to reduce dust formation, and these measures serve to further lower exposure. Studies and the nature of the petitioned PG reuse in road construction material compacted and/or encapsulated below pavement and above the water indicate that leaching to groundwater (or surface water) is likely not a complete exposure pathway. The relevant department of transportation has responsibility to ensure that construction, using materials including PG, is conducted in a manner that is judged adequately protective of the environment.

Limitations

This document summarizes work performed to date and presents the findings resulting from this work. The findings presented herein are made to a reasonable degree of engineering and scientific certainty. Exponent reserves the right to update this document as more information becomes available.

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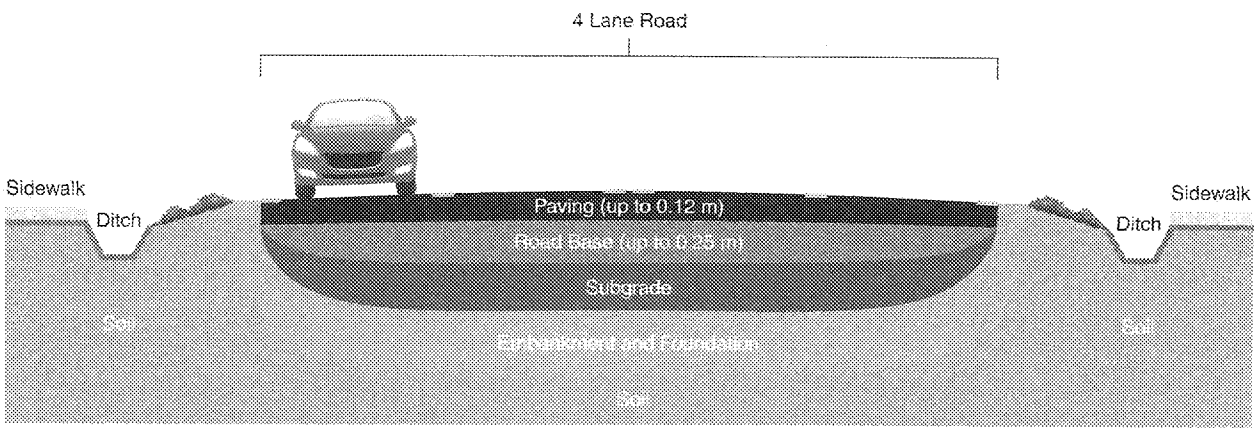

Figure 1. Typical roadway cross-section

Table 1. Concentrations of elements in phosphogypsum and comparison to EPA RSLs and U.S. soils

		Concentrations of Elements in Phosphogypsum (PG) from Literature Review														Comparison to EPA RSLs		Comparison to U.S. Soils	
		PG Stacks in Florida[a]	PG Stacks in Florida[b]	PG Stacks in Florida[c]		PG Ores from Idaho[c]			PG Produced in Louisiana[a]			PG Produced in Alberta Canada[f]	PG for U.S. and Worldwide[g]		Max Concentration in Literature Reviewed	EPA RSL for "Composite Worker Soil"[h]	Does Max Element Concentration in PG Exceed EPA RSL?	Average Surficial Soil Concentrations Conterminous U.S.	Does Max Element Concentration in PG Exceed Concentration in U.S. Soils?
Symbol	Element	Average	Average	Min	Max	Average	Min	Max	Value	Min	Max	Value	Min	Max					
Ag	silver	<1	<1.3	--	--	3.6	1.2	10.7	--	0.1	0.2	--	0.4	5	10.7 [c]	5,890	No	< 1 [i]	--
Al	aluminum	1,400	2,000	825	875	--	--	--	--	--	--	5,500	--	--	5,500 [i]	1,000,000	No	45,000 [i]	--
As	arsenic	40	0.84	1.7	2.1	--	<1	2	--	1	5	--	1.0	42	42 [g]	300	No	6.4 [i]	--
Au	gold	--	0.013	--	--	0.009	0.003	0.015	--	--	--	--	--	--	0.015 [b]	--	--	--	--
B	boron	3	--	22	50	--	<10	30	--	--	--	--	--	--	60 [b]	230,000	No	33 [k]	--
Ba	barium	7	<210	30.8	48.0	50	20	145	50	--	--	--	20	296	296 [g]	220,000	No	518 [i]	--
Be	beryllium	1	--	--	--	--	1	2	--	--	--	--	--	--	2 [c]	2,300	No	1.3 [i]	--
Bi	bismuth	1	--	--	--	--	--	--	--	--	--	--	--	--	1 [c]	--	--	0.34 [i]	--
Ca	calcium	--	21,000	113,200	171,200	--	--	--	--	--	--	583,000	--	--	583,000 [i]	--	--	15,900 [i]	--
Cd	cadmium	7	--	--	--	20	9	28	--	0.3	0.4	138	0.8	40	138 [i]	980	No	0.3 [i]	--
Ce	cerium	--	49	--	--	36	31	45	--	--	--	55	21	143	143 [g]	--	--	52.1 [i]	--
Cs	cesium	--	0.07	--	--	--	--	--	--	--	--	--	--	--	0.07 [g]	--	--	<5 [i]	--
Co	cobalt	2	0.58	--	--	--	<1	1	--	--	--	120	0.05	2.3	120 [i]	350	No	8.9 [i]	--
Cr	chromium	--	8.0	1.3	1.9	--	<10	70	--	2	5	--	1.8	75	75 [g]	1,000,000	No	38 [i]	--
Cu	copper	8	<82	1.9	2.0	27.5	10.2	41.7	--	--	--	185	2	195	195 [g]	47,000	No	17.9 [i]	--
Dy	dysprosium	--	<2.5	--	--	--	--	--	--	--	--	8	--	--	8 [i]	--	--	4.5 [i]	--
Er	erbium	--	<330	--	--	--	--	--	--	--	--	8	--	--	8 [i]	--	--	3.5 [i]	--
Eu	europium	--	1.5	--	--	1.2	1.1	1.4	--	--	--	3	1.1	3	3 [i,j]	--	--	2.1 [i]	--
Gd	gadolinium	--	170	--	--	--	--	--	--	--	--	10	--	--	170 [b]	--	--	6.1 [i]	--
Ga	gallium	--	<3.0	--	--	--	--	--	--	--	--	--	--	--	<3.0 [b]	--	--	11.1 [i]	--
Fe	iron	670	1,000	515	532	--	--	--	--	--	--	1,710	--	--	1,710 [i]	520,000	No	21,400 [i]	--
Hf	hafnium	--	1.9	--	--	--	--	--	--	--	--	--	--	--	1.9 [b]	--	--	--	--
Hg	mercury	--	0.40	--	--	--	--	--	--	0.02	0.05	--	0.005	10	10 [g]	45	No	0.05 [i]	--
In	indium	--	<0.14	--	--	--	--	--	--	--	--	--	--	--	<0.14 [b]	--	--	0.04 [i]	--
K	potassium	11	230	126	187	--	--	--	--	--	--	3,970	--	--	3,970 [i]	--	--	14,600 [i]	--
La	lanthanum	--	38	--	--	80.6	88.1	88.9	--	--	--	58	42	90	90 [g]	58	YES	26 [i]	YES
Lu	lutetium	--	--	--	--	0.41	0.36	0.51	--	--	--	1	0.3	0.4	1 [c]	--	--	0.8 [i]	--
Mg	magnesium	1,200	< 940	--	--	--	--	--	--	--	--	--	--	--	1,200 [g]	--	--	5,800 [i]	--
Mn	manganese	15	25	1.7	4.2	--	<2	10	--	--	--	174	3.5	20	174 [i]	26,000	No	612 [i]	--
Mo	molybdenum	18	11	--	--	--	<1	2	--	--	--	--	1	16	16 [g]	5,800	No	1.04 [i]	--
Na	sodium	250	520	--	--	--	--	--	--	--	--	9,710	--	--	9,710 [i]	--	--	8,100 [i]	--
Nd	neodymium	--	33	--	--	38	30	46	--	--	--	46	30	87	87 [g]	--	--	46 [k]	--
Ni	nickel	2	--	--	--	9	3	15	--	--	--	--	1.7	250	250 [g]	22,000	No	17.7 [i]	--
Pb	lead	1	--	2.7	3.5	5	3	7	--	2	10	--	0.5	16	16 [g]	800	No	25.6 [i]	--
Pt	platinum	<1	--	--	--	--	--	--	--	--	--	--	--	--	<1 [b]	--	--	--	--
Rb	rubidium	--	3.2	--	--	--	<10	20	--	--	--	--	--	--	20 [c]	--	--	66.2 [i]	--
Re	rhenium	11	--	--	--	--	--	--	--	--	--	--	--	--	11 [g]	--	--	--	--
Sb	antimony	100	0.25	--	--	0.5	0.3	0.5	--	--	--	121	--	--	121 [i]	470	No	0.53 [i]	--
Sc	scandium	--	<0.40	--	--	--	--	--	--	--	--	--	--	--	<0.40 [b]	--	--	6.8 [i]	--
Se	selenium	--	3.1	--	--	26	4	87	1	--	--	--	0.5	75	75 [g]	5,800	No	0.3 [i]	--
Sm	samarium	--	--	--	--	5.4	4.7	6.3	--	--	--	22	5	13	22 [i]	--	--	5.4 [i]	--
Sn	tin	4	--	3.8	6.3	--	--	--	--	--	--	381	--	--	381 [i]	700,000	No	1.6 [i]	--
Sr	strontium	10	600	--	--	640	610	670	--	--	--	1,700	10	1,118	1,700 [i]	700,000	No	158 [i]	--
Ta	tantalum	2	0.12	--	--	--	--	--	--	--	--	--	--	--	2 [g]	--	--	--	--

Table 1. (cont.)

		Concentrations of Elements in Phosphogypsum (PG) from Literature Review														Comparison to EPA RSLs		Comparison to U.S. Soils	
		PG Stacks in Florida[a]	PG Stacks in Florida[b]	PG Stacks in Florida[c]		PG Ores from Idaho[d]			PG Produced in Louisiana[e]			PG Produced in Alberta, Canada[f]	PG for U.S. and Worldwide[g]		Max Concentration in Literature Reviewed	EPA RSL for "Composite Worker Soil"[h]	Does Max Element Concentration in PG Exceed EPA RSL?	Average Surficial Soil Concentrations Conterminous U.S.	Does Max Element Concentration in PG Exceed Concentration in U.S. Soils?
Symbol	Element	Average	Average	Min	Max	Average	Min	Max	Value	Min	Max	Value	Min	Max					
Tb	terbium	--	1.0	--	--	1	0.8	1.2	--	--	--	1	--	--	1.2 [f]	--	--	1.2 [i]	--
Th	thorium	--	1.8	--	--	--	1	1	--	--	--	--	0.4	4	4 [g]	--	--	8 [j]	--
Ti	titanium	4,000	440	--	--	--	--	--	--	--	--	--	28	470	4,900 [g]	--	--	2,700 [j]	--
U	uranium	--	9.6	--	--	9.4	5.5	13.3	--	5	10	--	0.5	13.8	13.8 [g]	230	No	2.1 [j]	--
V	vanadium	19	4.6	1.2	2.3	20	10	40	--	--	--	--	2	40	40 [g]	5,800	No	60 [j]	--
W	tungsten	30	<0.91	--	--	--	--	--	--	--	--	--	--	--	30 [g]	930	-	1.3 [j]	--
Y	yttrium	2	--	--	--	110	100	120	--	--	--	116	2	156	156 [g]	--	--	14.8 [j]	--
Yb	ytterbium	--	2.6	--	--	2.5	2.5	3.5	--	--	--	6	2.1	3.2	6 [f]	--	--	3.1 [k]	--
Zn	zinc	9	<340	3.1	5.3	50.0	18.1	112.0	--	--	--	112	4	315	315 [g]	350,000	No	66 [j]	--
Zr	zirconium	10	--	--	--	--	<10	110	--	--	--	--	10	110	110 [g]	58	YES	180 [k]	No

Note: All units are mg/kg; some values were reported in weight percent (weight percent x 10,000 ppm = mg/kg).

-- - value not reported
EPA - U.S. Environmental Protection Agency
PG - phosphogypsum
RSL - regional screening level
U.S. - United States

[a] May and Sweeney (1984a), Table 11. "...the data summarized concentrations only in cores where elements were detected" (p. 137).
[b] May and Sweeney (1984b), Table 12.
[c] Mosfary (2011), Table 4-1. Reported values are mean of three samples taken from each of four locations.
[d] Lutner et al. (1993), Table II.
[e] Taha et al. (1992), Table 2.
[f] Walawalkar (2016), Tables 5 & 6
[g] IAEA (2013), No. 78., Table 55.
[h] The lowest RSL is used, non-cancer or cancer, and adjusted to a target risk of 1E-04. Chemicals without published RSLs are not screened.
[i] RSL values above 1,000,000 were set to 1,000,000.
[j] Smith et al. (2013), Table 2. The mean of the surface soil samples collected from a depth of 0 to 5 cm in the conterminous United States.
[k] Shacklette and Boerngen (1984), Table 2, geometric mean.
[l] Tyler (2004), Table 1.

Table 2. Concentrations of elements in phosphogypsum, fly ash, and portland cement

Symbol	Element	Max Concentration in PG from Reviewed Literature	Median Reported Concentration in Fly Ash	Median Reported Concentration in Portland Cement
Ag	silver	**10.7**	0.55	8.6
Al	aluminum	5,500	**87,833**	26,250
As	arsenic	42	**50.1**	12.4
Au	gold	0.015	--	--
B	boron	60	**403**	42.5
Ba	barium	236	**1,189**	205
Be	beryllium	2	**10.5**	0.98
Bi	bismuth	1	--	--
Ca	calcium	583,000	--	--
Cd	cadmium	**138**	1.3	0.03
Ce	cerium	143	--	--
Cs	cesium	0.07	--	--
Co	cobalt	**120.0**	45.3	10.0
Cr	chromium	75	**107**	58.6
Cu	copper	**195**	108	36.0
Dy	dysprosium	8	--	--
Er	erbium	8	--	--
Eu	europium	3	--	--
Gd	gadolinium	170	--	--
Ga	gallium	<3.0	--	--
Fe	iron	1,710	**27,514**	N/A
Hf	hafnium	1.9	--	--
Hg	mercury	**10**	0.17	0.01
In	indium	<0.14	--	--
K	potassium	3,970	--	--
La	lanthanum	90	--	--
Lu	lutetium	1.0	--	--
Mg	magnesium	1,200	--	--
Mn	manganese	174	219	**465**
Mo	molybdenum	16	**16.3**	5.0
Na	sodium	9,710	--	--
Nd	neodymium	67	--	--
Ni	nickel	**250**	76.7	25.0
Pb	lead	16	**55.0**	6.3
Pt	platinum	<1	--	--
Rb	rubidium	20	--	--
Re	rhenium	11	--	--
Sb	antimony	**121**	6.2	0.10
Sc	scandium	<0.40	--	--
Se	selenium	**75**	8.8	2.0
Sm	samarium	22	--	--

Table 2. (cont.)

Symbol	Element	Max Concentration in PG from Reviewed Literature	Median Reported Concentration in Fly Ash	Median Reported Concentration in Portland Cement
Sn	tin	381	--	--
Sr	strontium	**1,700**	795	N/A
Ta	tantalum	2	--	--
Tb	terbium	1.2	--	--
Th	thorium	4	--	--
Ti	titanium	4,000	--	--
U	uranium	**13.8**	5.5	N/A
V	vanadium	40	**267**	64.0
W	tungsten	30	--	--
Y	yttrium	156	--	--
Yb	ytterbium	6.0	--	--
Zn	zinc	**315**	141	64.0
Zr	zirconium	110	--	--

Source: U.S. EPA (2014). Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard, Table 2.1.

Note: All units are in mg/kg.
Values in bolded text that are outlined represent the highest concentration between the maximum reported PG concentration from the literature review, the median concentration in fly ash, and/or the median concentration in Portland cement for elements that report more than one of these values.

-- - not reported
N/A - not applicable
PG - phosphogypsum

MEMO

ARCADIS Design & Consultancy for natural and built assets

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ENVIRONMENT

From:
Douglas Chambers

Date:
April 7, 2020

ARCADIS Project No.:
30006877

Subject:
Response to EPA Questions issued on Jan 16, 2020

In response to a set of questions from the United States Environmental Protection Agency (USEPA), related to the risk assessment report submitted in October 2019[1] as support to the petition for beneficial use of phosphogypsum, Arcadis has prepared the following responses and comments.

For each paragraph provided by EPA in their questions, Arcadis has provided a response. Where a full response could not be included in this memo, reference to additional information is provided.

Modeling approach:

1. USEPA: The developers of the risk assessment chose to use a deterministic (vs. stochastic) model using discrete input parameters judged to be typical. From the standpoint of model development, this was a simpler—and potentially clearer—approach. However, a probabilistic approach to model input parameters could have provided the opportunity to incorporate uncertainty and variability into the model, and also could have explicitly included other road designs or variations on road design.

Arcadis: Arcadis intentionally chose a deterministic approach as a full probabilistic approach is quite challenging to present to the public. We recognize that there are variations in scenarios and assumptions and therefore, we intentionally made assumptions and selected parameters that in our view overestimate the potential exposures and doses bracketing the risk. Moreover, the models are linear for key parameters, such as Ra-226 concentration and exposure duration and hence readily scalable. In addition, we believe that the current approach estimates a reasonable maximum exposure (RME).

The RME scenario considers the highest exposure that might reasonably be expected to occur, one that is well above the average case of exposure but within the range of possibility and is intended to provide the basis for estimating the maximum individual risk (MIR). Use of the RME to model baseline human health risks is a conservative approach, in that it yields upper-bound cancer risk and non-cancer hazard estimates (USEPA, 1989). The "intent of the RME is to estimate a conservative exposure case (i.e., well

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[1] Arcadis 2019. *Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum*, Report to The Fertilizer Institute, October.

above the average case) that is still within the range of possible exposures."[2] Each exposure factor used to estimate the RME should be selected "so that the resulting estimate of exposure is consistent with the higher end of the range of plausible exposures" (citing EPA 1991 guidance).[3]

A National Academy of Science (NAS) Committee reviewing EPA's regulation of technologically enhanced naturally occurring radioactive material (TENORM) recommended that EPA "should use exposure and dose risk assessments that are "reasonably realistic"" in developing standards for exposure to the various types of low level naturally occurring radiation.[4] "The Committee defined "reasonably realistic" as "not … .intended to greatly overestimate or underestimate actual effects for the exposure situation of concern."" and EPA agreed with the Committee's recommendations.[5] The use of reasonable exposure assumptions is supported by the courts, which have long held that exposure assumptions used "must bear some rational relationship" to the actual conditions, and disallowed unduly conservative approaches.[6]

The current deterministic approach of the Risk Assessment focusing on RME scenarios to estimate MIR, provides the best alignment with the purpose of the RA, to compare predicted risks from the proposed use of PG against the risk threshold that is consistent with the determination of a 'safe' level. Overall, the choice of parameters other than those used in the current risk assessment are more likely than not to result in lower doses and risks to the receptor.

Probabilistic (stochastic) approaches would provide added information of the potential variability and uncertainty of the risk at lower risk levels, but overall would not change MIR substantially. In addition, the

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[2] EPA, EPA: Risk Assessment Guidance for Superfund: Volume III - Part A, Process for Conducting Probabilistic Risk Assessment, 7-1 (2001), *available at* https://www.epa.gov/sites/production/files/2015-09/documents/rags3adt_complete.pdf. See also Interstate Technology Regulatory Council, Decision Making at Contaminated Sites, Issues and Options in Human Health Risk Assessment at 6.1.1 (2015), *available at* https://www.itrcweb.org/risk-3/Default.htm#6.%20Exposure%20Assessment.htm#6.1__Determining_Appropriate_Exposure_Factors%3FTocPath%3D6.%2520Exposure%2520Assessment%7C6.1%2520%2520Determining%2520Appropriate%2520Exposure%2520Factors%2520%7C_____0 (ITRC, Decision Making at Contaminated Sites), citing EPA Guidance, which states that "[t]he RME . . . can be defined as "the maximum exposure that is reasonably expected to occur within a potentially exposed population."

[3] Id.

[4] EPA, Report to Congress, Evaluation of EPA's Guidelines for Exposures to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), 15 (June 2000) (describing a National Academy of Sciences report on TENORM), available at https://www.epa.gov/sites/production/files/2015-04/documents/402-r-00-001.pdf (EPA Report to Congress Re: TENORM).

[5] Id.

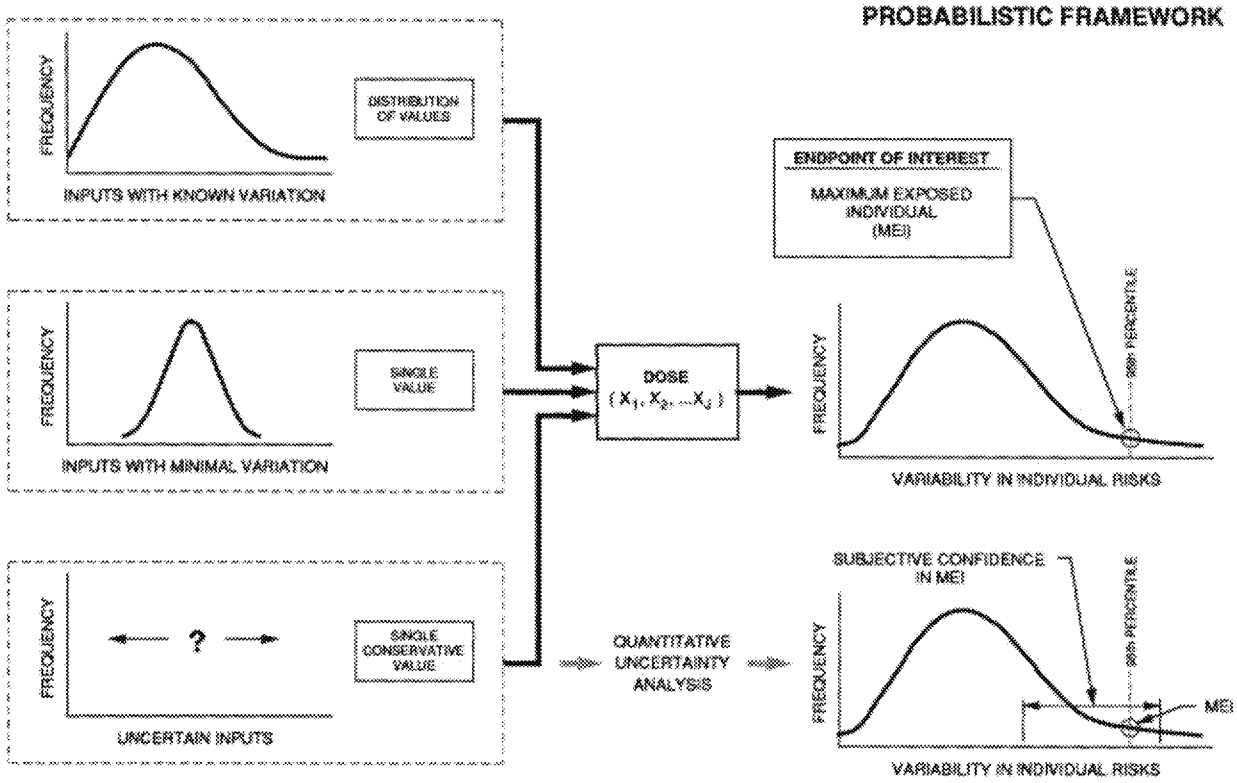
[6] *Leather Indus. of America v. EPA*, 40 F.3d 392, 405 (D.C. Cir. 1994).

complexity of developing subjective probability distribution functions for the model parameters can be quite difficult and often challenging to explain to the general public and thus the probabilistic approach was not selected for the assessment. The modelling approach using deterministic parameters to calculate RME dose and risk estimates was reviewed with EPA in advance of the Risk Assessment.

To illustrate the possible output of a probabilistic approach Figure 1.1 is provided below. The deterministic approach targets calculations for the Maximum Exposed Individual (MEI) or person in the RME scenario, often someone at the upper-end (approximately 90th to 95th percentile) of dose (risk). EPA guidelines state that the assessor may derive a high-end estimate of exposure by using maximum or near maximum values for one or more sensitive exposure factors, leaving others at their mean value.[7] Based on our experience with regulatory decisions, the MIR from a deterministic assessment as performed in our October 2019 risk assessment would be generally comparable to these upper limits of dose (risk).

FIGURE 1.1

PROBABILISTIC FRAMEWORK



[7] Exposure Factors Handbook: 2011 Edition at (2011) https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252.

2. USEPA: 61.206(b)(8) requires the risk assessment to include an estimate of the risk distribution.

Arcadis: The original NESHAPS (December 15, 1989 Federal Register) defines a risk distribution estimate as how many persons within a certain distance (e.g. 80 km) of a source of pollutant emissions are at an increased level of individual risk. This requires an estimate of the dispersion of a radioactive pollutant, from a source and an estimate of the population within that distance.

EPA clarified at our meeting that providing more risk distribution information was information on how the risk varied with the "variation of the geometry of exposure" and with different exposure time frames. The RME approach utilized in the risk assessment also serves as a reasonable upper bound on the risk distribution and is a readily accepted approach for not only representing the maximum exposures but also providing insight into risks to people who might be exposed to PG. RMEs are constructed to likely overestimate risks for highest exposure situations; actual risks to these people and risks to the rest of the population would all be lower. Knowledge is relied upon for setting such bounds for the RME and when bounded values are used in calculation, the results are conservative (i.e., higher) estimates of the risks.

Although risk distribution was used in 1989, many EPA risk assessments (including the 1992 BID risk assessment) do not utilize risk distribution. The general risk distribution discussed below is acceptable in this situation.

The radiological "pollutants" associated with PG in roads are direct gamma emissions, particulates, and radon. As shown in the risk assessment, external gamma is by far the dominant source of dose, followed by radioactive particulate emissions and radon.

The gamma exposure dose decreases rapidly with distance, for example at one road used in a Florida Institute of Phosphate Research (FIPR) study, the exposure was indistinguishable from background levels at 50 feet from the road centerline (FIPR, 1989[8]). For the nearby residential exposure scenario, the risk calculated in the October 2019 radiological risk assessment calculated that radiological exposure is always below background levels and reduces with distance from the road, becoming indistinguishable from the variability of background at 50 feet from the road's edge.

Background terrestrial radiation has been shown to have wide variability between states and within states in the US (S. Cohen & Associates 2005)[9].

> *It is instructive to note that not only are there substantially large differences in the average terrestrial doses among states (e.g., 14.3 mrem/yr in Florida versus 42.6 in Colorado), but there are also large differences in the average terrestrial dose rates among cities within a state. For example, in Colorado, the average terrestrial dose rate in Pueblo is 29.2 mrem/yr, while in Denver it is 57.4 mrem/yr. In Las Vegas, Nevada, the terrestrial dose rate is 12.7 mrem/yr, while in non-urban regions of Nevada it is 29.2 mrem/yr.*

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[8] Chang, Wen F., Chin, David A., and Ho, Robert, 1989. Phosphogypsum For Secondary Road Construction, University of Miami, For Florida Institute of Phosphate Research, Publication No. 01-033-077, 01-041-077.

[9] S. Cohen & Associates. 2005. Assessment of Variations in Radiation Exposure in the United States Contract Number EP-D-05-002 Work Assignment No. 1-03. Prepared for U.S. Environmental Protection Agency Office of Radiation and Indoor Air 1310 L Street, N.W. Washington, DC 20005.

The USNRP in Report No. 160[10] confirms the range of background terrestrial radiation dose in the USA is variable, depending on local geology and other factors, and ranges from about 10 mrem/y to more than about 40 mrem/y.

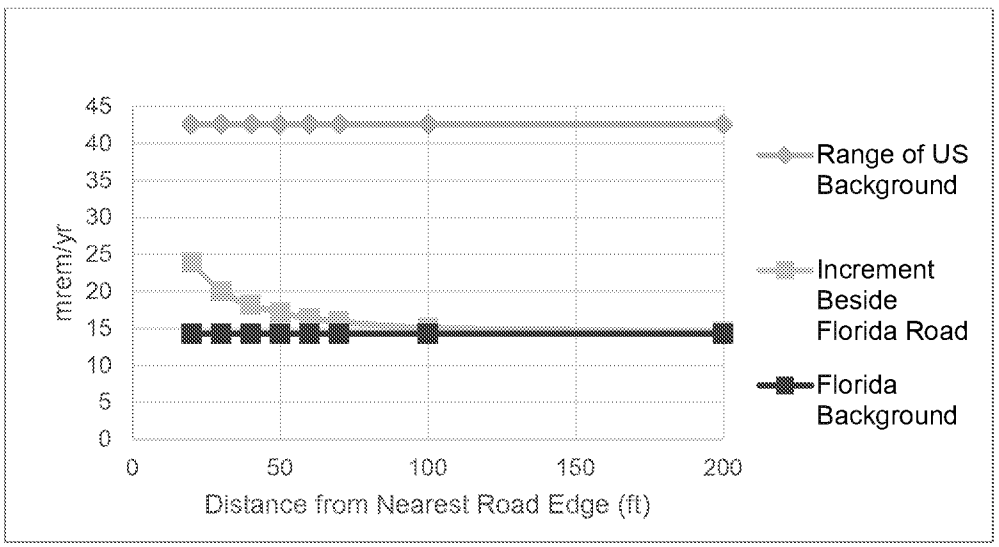
Figure 2 below combines the (notional) background radiation dose in Florida with the incremental dose from a PG road. The figure also displays the upper range of background radiation dose in the US (for Colorado). This clearly shows that dose from a PG road is inconsequential relative to background for distances typical for the closest residence. Further it shows that at distances reasonable for a second closest residence (approximately 100 feet) the dose is essentially zero.

These distances are well short of the 80 km values used in the 1989 risk distribution. Therefore, the contribution to a risk distribution is zero beyond that distance.

Similarly, it was shown in the Risk Assessment that the dose from inhalation and ingestion of particulates was also quite low, less than 10% of the total dose for the worker in the center of the road. As particulate concentration is highest on the road in the construction zone, particulate concentrations reduce with distance from the road and will quickly reach background levels again resulting in zero dose contribution to the risk distribution. In addition, particulate generation is only relevant during construction which occurs for a limited duration in any one location.

Last, is the radon generated from the road. Outdoor radon is quickly disbursed to background levels within a few tens of feet from the road, see for example the measurements on roads constructed with PG. (FIPR, 1989, "Phosphogypsum for Secondary Road Construction"). As previous, the calculated contribution to the risk distribution from radon is zero.

Figure 1 – Incremental External Gamma Dose with Distance Compared to Terrestrial Background



[10] NCRP Report No. 160, Ionizing Radiation Exposure of the Population of the United States

The following table provides summary comments on risk distributions by exposure pathway. The table explains the limited applicability of the RME scenario and the potential for lower exposures and doses to occur for a broader population.

SUMMARY OF RISK DISTRIBUTION FROM USE OF PG IN ROAD CONSTRUCTION		
Exposure Scenarios	RME (small number of people)	Potential Lower Exposures and Risk Distribution
Road Construction Worker	Risk: 0.5 in 10,000 Few if any workers would fit the RME assumption of 100% of workdays on the uncovered road base. The RME worker is exposed to less than 7% of background levels (for all members of the public.	Much less than 0.5 in 10,000 Most workers are expected to spend less than 100% of the workday on the uncovered road base. Dose and risk reduce linearly with reduced exposure time. Time on a covered road base was shown in the Risk Assessment to be a factor of 5 lower. The dose would range down to essentially zero for management and supervision who would spend very limited time on the road and out of vehicles. The number of workers in a road crew is estimated to be as small as 6 – 8 workers, which limits the risk distribution to a small group.
Road User	Risk: 0.1 in 10,000 This RME is assumed to be a heavy user of the road spending 2 hours daily on the road. This scenario is unlikely to occur until far into the future if PG roads become widely available. Until then it is unlikely a commuter would be able to spend this amount of time on a PG road. In the extreme case, the RME road user is exposed to less than 0.3% of background.	Well below 0.1 in 10,000 Most road users will be on the road for much less than two hours per day. Dose and risk reduce linearly with reduced exposure time. Initially when PG use in roads is newly implemented the availability of PG roads will be low reducing the opportunity to have substantive usage time. As the total amount of PG roads increase the risk distribution would increase with additional road users and cumulative usage time. The overall risk to an individual however, is not expected to exceed the RME estimates. Most road users would still have limited time on PG roads and this results in a proportionally limited dose and risk. The overall number of road users is difficult to specify as it depends on several factors including

		the road type and location relative to populated areas. However, the dose to road users would remain a small fraction of that from unavoidable background radiation.
Truck Driver	Risk: 0.5 in 10,000 The Truck Driver RME is limited to workers who participate in PG road construction projects. The assumptions for this scenario are set to estimate the upper end of likely dose and risk for this work. The RME Truck Driver is exposed to less than 6% of background levels.	A truck driver that has less than an RME exposure has lower risk than 0.5 in 10,000. There are a limited number of truck drivers involved in a road construction project. In addition, truck drivers will support numerous construction projects during the course of a year and many not involving use of PG. This limits the risk distribution for this exposure pathway to a relatively small number of people. In many cases, Truck Drivers will not work on PG road construction as much as assumed for the RME, resulting in a lower dose and risk.
Nearby Resident	Risk: 0.08 in 10,000 The Nearby Resident RME is based on extreme assumptions that are unlikely to apply to all residents of a PG road. The assumptions include close exposure to the road and long durations of residency throughout the exposure period. Based on these assumptions the Nearby Resident RME is exposed to 0.2% of background levels.	Most residents near a PG road would be exposed to much lower doses and risk, well below 0.08 in 10,000. Radiation levels from a PG road decrease rapidly with distance from the road and become indistinguishable from background at 50' to 100'. See figure and discussion. As a result, most residents immediately beside a PG road would be exposed to much less than the RME risk level, and residents beyond the immediately adjacent properties would experience essentially zero incremental risk. The overall risk distribution would depend on the overall length of the PG road and population density along the road but is limited to only those locations immediately beside the PG road.
Utility Worker	Risk: 0.004 in 10,000 The Utility Worker RME scenario represents an extreme case where a worker needs to disrupt the road for road or utility maintenance. The assumptions use worst case conditions to estimate the risks	Most Utility Workers would be exposed to risk much less than 0.004 in 10,000. Most utility repair requirements would involve exposure scenarios below those assumed for the RME conditions, due to smaller trenches and exposure areas, or shorter durations.

	and are limited to workers in a trench in a PG road and meeting the other exposure assumptions. The RME Utility Worker is exposed to approximately 0.3% of background levels.	The number of individuals entering a trench in a PG road is also limited based on the uniqueness of the work and the limited space. As a result, the risk distribution for the Utility Worker is limited to a small number of individuals.
Reclaimer Extreme Scenario	Reclaimer is an extreme scenario well beyond an RME assumption and therefore, is not appropriate to determine whether the use of PG is safe. This example for ultimate disposal was selected due to the use by EPA in 1992. Risk: 0.4 in 10,000 The Reclaimer would be exposed to approximately 1% of background levels. (total exposure of 78 mrem compared to a Background of 8,060 mrem over 26 years)	The Reclaimer scenario represents an extreme situation that is unlikely to even occur as described. As a result, the risk distribution is effectively zero. More realistic situations for the ultimate disposal of the road include continued use of the road as a road, or reuse of the PG road base for a new road, if the road was to be relocated or realigned. In the extreme case where a road is abandoned and then the land is reused for other purposes, the land preparation activities will realistically result in blending and mixing of the road base to levels that are indistinguishable from background levels. Overall, the risk distribution would be effectively zero.

In summary, the risk distribution from road construction is negligible, beyond the individuals who are on or immediately beside the road, as assessed in the Risk Assessment document.

3. USEPA: No discussion of uncertainty in model outputs is provided. There is no discussion of uncertainty around model input parameters, with the minor exception of uncertainty of the dose-to-risk conversion factor (p. 1-1). Except for briefly mentioning variability in naturally-occurring background radiation (p. 3-4), the risk assessment does not address variability around model parameters such as exposure factors, activity concentrations, exposure duration, etc.

Arcadis: The Risk Assessment was developed to examine a conceptual road design, to provide an estimate of the upper end RME risks associated with PG use in roads. It is impractical to perform a risk assessment that uses different values for every conceivable road design. Neither the 1989 nor the 1992 BID risk assessment considered every conceivable road design. Many features (such as the number lanes) do not affect the potential exposure. Many other road design features were set at an upper bound RME value and any design that uses different value will reduce the risk or not be an RME.

The following is an example list of factors utilized to minimize the impact of any uncertainties.

- We assumed that EPA's 1992 BID risk assessment used high end assumptions as was the policy at the time. In general, the 2019 radiological risk assessment is more conservative (i.e., results

in higher exposures) than the 1992 BID. The 2019 radiological risk assessment used the same exposure scenarios plus two new exposure scenarios.

- In conjunction with the submission of the Petition, TFI members agreed to perform radiological testing of PG. Nine PG stacks located in Central Florida (where the highest Ra-226 levels would be expected), Louisiana, and the Western U.S. with ten samples taken from each stack, for a total of 90 samples.4 A summary of the results is as follows:
    - The average Ra-226 concentration of all 90 samples is 18.6 pCi/g.
    - Ra-226 concentrations in individual samples range from 6.3 pCi/g to 27.9 pCi/g.
    - The average Ra-226 concentration from the 2019 stack sampling (18.6 pCi/g) is below the radioactivity concentration limit of 35 pCi/g proposed in the Petition, and well below the average Ra-226 concentration of 148 pCi/g that corresponds to an EPA safe risk level of 3 in 10,000.
    - No individual concentration from the 2019 stack sampling (with concentrations ranging from 6.32 pCi/g to 27.9 pCi/g) exceeds 35 pCi/g.
- The EPA 1992 BID assumed a 1:2 dilution of PG with soils for a road base concentration of 10 pCi/g. The October 2019 risk assessment utilized less dilution (1:1 PG:soil).
- The EPA 1992 BID assumed the road base was 0.25 m thick and 30 feet (9.15m) wide and that the road base is covered with a 0.12 m (5 in) thickness of asphalt. The October 2019 risk assessment utilized a road thickness of 0.25 m (the same as in 1992).
- The EPA 1992 BID assumed PG in a concrete road incorporates 15% PG by weight and 0.12 m thick (5 in) and 24 feet wide (7.32 m). The October 2019 reviewed road base design criteria and concluded 15% was a high-end criterion.
- The EPA 1992 BID used exposure to the critical population group member (nearby resident 100 m (i.e., 328 ft) from the edge of the road). The October 2019 radiological risk assessment calculates the radiation levels at 50 feet from the edge of the road.
- The current risk assessment assumes a worker moves around over the road surface and is exposed at the average of the gamma fields at the center and edge of the road, which is more reasonable than assuming a worker never moves for 5 years. The stationary worker is not realistic or reasonable, therefore it is not an RME.
- The 1992 EPA risk assessment used a 0.6 shielding for the road user, but rather than determine the degree to which vehicles have changed the amount of metal in the under carriage of cars, the current risk assessment takes no credit for shielding provided by the vehicle which however would provide some level of shielding which is a conservative assumption and could reasonably be considered.
- The current risk assessment considered two receptors beyond those considered in the 1992 BID (truck driver and utility worker).

Given the fact that each of the exposure assumptions are RME (including road design parameters), the uncertainty is addressed with the risk assessment without having to perform numerous risk calculations that will simply confirm the nature of the RMEs utilized. If EPA identifies any road design factors that increase the radiological risk and are RME, the Petitioners will evaluate it. In summary, as described in the first item under Modelling Approach above, the selection of deterministic parameters was done at the conservative end of the expected range of uncertainty, to provide calculations tending to overestimate expected results.

Conceptual road model:

4. USEPA: What is the generic composition (in more detail) of a road? For example, if road base is to be composed of a mixture of soil and PG, what are the ranges of composition of the soils to be used (e.g., organic carbon content, clay contents, moisture).

Arcadis: The Risk Assessment is intended to provide a conceptual exposure model of PG use in roads and is not linked to a specific road segment approval.

The selected example road was a four-lane county road with two lanes in each direction. This type of road is common in rural, suburban and urban settings and represents the type likely to be constructed by state and local governments who can employ PG during construction.

Choice of this road type permits evaluation of construction workers, nearby residents, bicyclists and motorists, and utility workers. The road dimensions are 15 m wide (about 12 feet [ft] per lane) and 100 m long (segment length) for modeling exposures. The thickness of the road base containing PG and road surface (i.e., pavement) are 0.25 m and 0.12 m respectively consistent with the EPA BID (1992).

The road base in the example road was selected to be PG mixed with in-situ soil, as it is the most probable choice to mix with PG. This soil would likely be used whether or not PG was used in the road base mix and is not considered as a risk variable. The soil-PG mixture will be compacted as part of the road construction process leading to high densities in the road base. Other site-specific soil parameters were not defined and are generally less important to the overall risk calculations. Specifically, carbon or clay content and moisture levels are not key factors in the risk determination (i.e., the radiation levels do not vary significantly based on these factors. Gamma ray attenuation for a fixed thickness of shielding is based on the density of the material being penetrated and to a lesser degree the chemical composition. The gamma source strength for a large slab of gamma emitting materials is proportional to the source strength (disintegrations per cc per sec) and inversely proportional to the mass attenuation coefficient[11]. The first term, source strength, can be rewritten as Bq/g x g/cc (pCi/g x g/cc). The second term, mass absorption coefficient is the linear attenuation coefficient divided by density. Both terms are dependent on density (i.e., g/cc or equivalent units). Thus, for practical purposes, the density of the source material is the key factor irrespective of the characteristics of the source material per se.

5. USEPA: What is the basis for limiting phosphogypsum to 50% in the road base? Is there a geotechnical reason, such that structural stability suffers at higher proportions? Is there an optimal range for durability? Alternatively, would administrative controls need to be put in place to maintain this limit during construction? Would an end-user need to address the administrative controls in a specific use request?

Arcadis: Available research on experimental roads reported PG:soil ratios in the range of 1:2 PG:Soil. The EPA in their 1992 BID used a 1:2 mix of PG:sand. This is also the PG ratio in the Polk and Columbia county roads[12] constructed with input on the design and testing of the roads from the University of Miami and the Bureau of Materials & Research, the Florida Department of Transportation.

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[11] Rockwell, Theodore, July 1956. "Reactor Shielding Manual". U.S. Atomic Energy Commission, First Edition.

[12] Chang, Wen F., and Mantell, Murray I., 1990. Engineering Properties and Construction Applications of Phosphogypsum, University of Miami, Phosphate Research Institute, ISBN No. 87024-328-4.

In a study by W.F. Chang et at (Chang, Wen F., Chin, David A., and Ho, Robert, 1989)[13], various ratios of PG to soil were studied. California Bearing Ratio CBR test were conducted on ratios of PG: sand ranging from 100% sand to 100% PG. The PG to sand mixtures showed all mixes had CBR values higher than sand or PG separately. Various radios of PG to soil were used in sections of an experimental road in Polk County Florida. The PG was rototilled into the soil to various depths, A portion was also covered by an asphalt coat. These studies indicate that there is no reason to limit the quantity of PG to be used in a road. The limiting factor would be the measured compressive strength and durability of the admixtures prior to their use in the road. Further studies could establish guidance on the range of PG to soil ratio allowed for various soil types. A 50:50 mixture of PG and local construction materials such as sand or soil is likely to be an overestimate of the actual mix

As noted in the figure below, road design parameters and specifications are better optimized at lower PG:soil ratios. To be conservative of potential risks, the risk assessment considered the upper end of likely reasonable mixture ratios. As stated in previous comments, this parameter provides a linear impact on the risk results. So, if alternate concentrations of PG are desirable, the risks can be easily extrapolated up or down from the existing calculations.

The amount of PG that would be used in a lane/mile of road base depends on many things such as: thickness of the road base, the percent PG in the road base, density of the PG, width of a "lane". In the end, the appropriate County, State or Federal road authority will have to approve the specifications of the road base used in the design. However, to illustrate the concept, consider a road where 1) lane width is 25 feet, 2) the maximum thickness of the road base mix is 12-inches, 3) the maximum percent PG in the road base is 50%, 4) the dry density/95% proctor can be based off the attached Figure 3.6 from Chang and Mantell 1990[14].

The Figure 3.6 Maximum density curve is based on a PG soil mix, it provides the highest density with PG at 1/6 of the mixture – which can then be extrapolated using the curve for a half/half mixture. Using this range yields a 95% proctor density of 1.9 to 1.98 grams/ cubic centimeter which converts to 118.6 to 123.6 lb/cubic ft.

That said, a 25 ft wide lane for one mile, would require about 3,900 to 4,100 tons of PG per mile, rounded to 4,000 tons/mile.

However, it is the concentration of Ra-226 in the road base that determines the gamma radiation levels. For example, a road with PG at 1/6 of the mixture as described above would have a Ra-226 concentration 3 times lower than the calculations provided in the 2019 risk assessment, and result in doses and risks 3 times lower. As previously indicated, the 2019 risk assessment assumed a 1:1 mix of PG and local soils. This is considered a reasonable upper bound for such a mixture and hence alternative mixtures will have lower concentrations of Ra-226 than were assessed in the 2019 risk assessment and hence, it follows that the doses and risks would also be lower.

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[13] Chang, Wen F., Chin, David A., and Ho, Robert, 1989. Phosphogypsum For Secondary Road Construction, University of Miami, For Florida Institute of Phosphate Research, Publication No. 01-033-077, 01-041-077.

[14] Chang, Wen F., and Mantell, Murray I., 1990. Engineering Properties and Construction Applications of Phosphogypsum, University of Miami, Phosphate Research Institute, ISBN No. 87024-328-4.

36 PHOSPHOGYPSUM

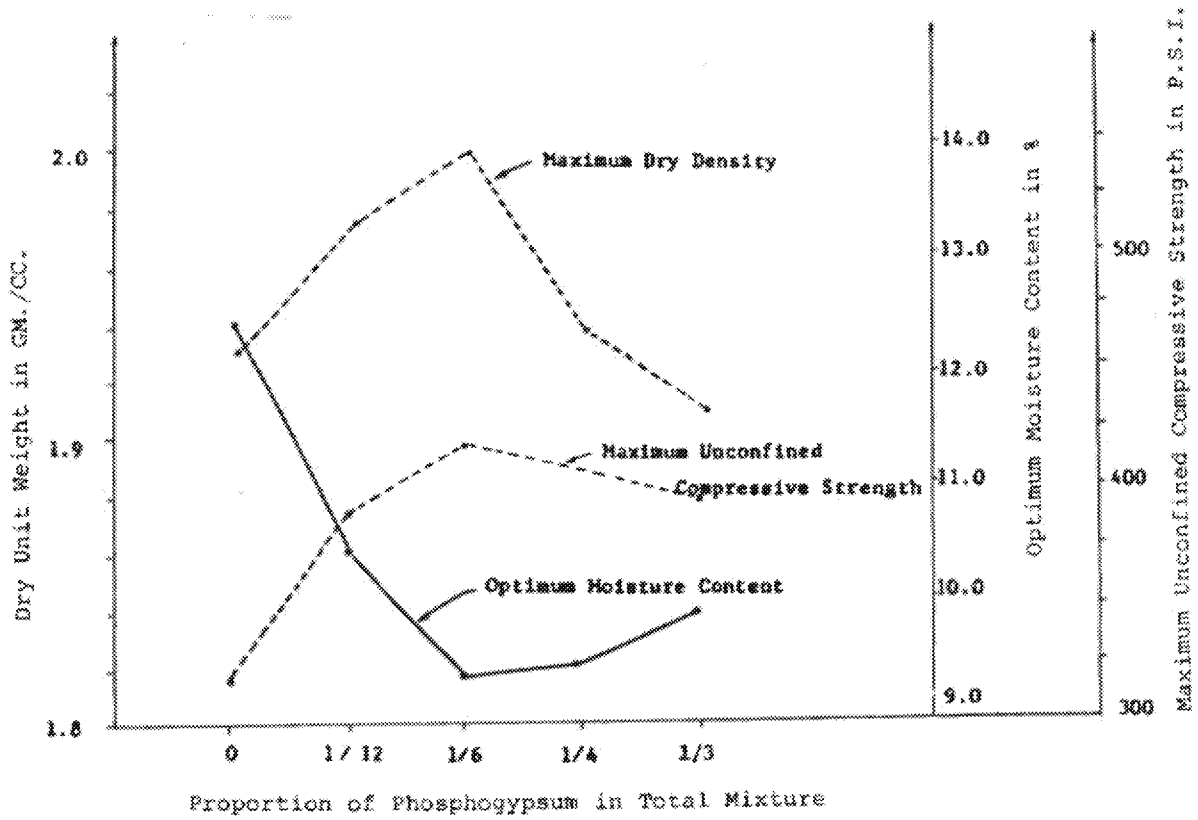

Figure 3.6 Variation in the maximum unconfined compressive strength, optimum moisture and maximum dry unit weight with change in the proportion of phosphogypsum in the various mixtures of clayey sand, sand and phosphogypsum.

6. USEPA: Reviewers had questions related to the conceptual model for the road design, specifically the restriction of the phosphogypsum-containing layer of road base to the area under the pavement. A road model used by the U.S. Federal Highway Administration, "Tech Brief: Bases and Subbases for Concrete Pavements," FHWA-HIF-16-005 (https://www.fhwa.dot.gov/pavement/concrete/pubs/hif16005.pdf) shows a road base which extends 3 to 4 feet (91 to 122 cm) beyond the road cover on each side of the road. In this case, all scenarios would need to account for some gamma exposure from road base material that is not shielded by pavement, and the possibility that phosphogypsum may become airborne at the uncovered edges of the road base.

Arcadis: The risk assessment provided an examination of a conceptual road design with risks estimated for scenarios and exposure pathways expected to be the most dominant. The road design in the risk assessment approximated road design characteristics and plausible exposure scenarios for various types of roads. While some large highways may have exposed shoulders, those roads are unlikely to have pedestrians, cyclists or houses in close proximity. Suburban and urban roads represented a plausible

scenario which maximizes exposures for the dominant external gamma pathway. Airborne dust from exposed shoulders is not expected to be a dominant pathway due to the binding properties of PG and the limited potential for substantive intake. Further, road shoulders typically become infilled with vegetation which also suppresses dust.

To explore this question, Arcadis considered the dose and risk impacts for a conceptual road with a 4-foot uncovered shoulder. We estimated results that are not substantially different from that of the original conceptual design of a 15-meter-wide road. Consider the worst case a worker at the center of the road. Gamma rays emitted from the strip (consider the leading or close edge or 7.5 m from the center) would need to travel at an extreme angle (~7.6 degrees) to impact a worker at the center of the road at the dose point (one meter above the surface. From the far edge (8.7 m form the center) the angle is 6.6 degrees. Assuming gamma rays are emitted isotropically, then about 1% of the additional emitted gamma rays (1/90) strike the worker.

Additional gamma calculations were also done with RESRAD for an uncovered road shoulder as described below to confirm the above estimations. Two cases were run with all the parameters fixed with the exception of the area. The original area was 15 m by 100 m, the adjusted area was 17.5 m by 100 m. Table 1 presents the exposure for a worker at the road center in both cases. As indicated the maximum contribution to the dose is external gamma. The increase in dose for external gamma is about 1.5%

Table 1 Dose to a maximumly-exposed worker at the center of a road with constructed with PG

	Direct exposure mrem/year	Inhalation dose mrem/year	Inhalation Dose mrem/year	Total Dose mrem/year
Original Road (15 m x 100 m)	26.11	0.1423	1.918	28.170
Adjusted Road (17.5 m x 100 m)	26.51	0.1465	2.004	28.661
Increase %	1.5%	2.9%	4.4%	1.7%

A similar calculation can be performed with the exposure point at the edge with similar results. The conclusion is that the 3- to 4-foot (i.e., 1 m to 1.2 m) strip along the road has minimal increase in the dose and final risk.

7. USEPA: Are assumptions related to durability and weathering of roads based on documented experience? What are the assumptions regarding the frequency of repaving or other road maintenance/replacement? Are they correlated to the type of road and traffic projections? Would an end-user need to account for such assumptions in a specific use request?

Arcadis: Road maintenance related to weathering roads was not explicitly assessed in the 2019 risk assessment, nor was road maintenance assessed in the EPA 1992 BID. This scenario is not deemed to be an RME condition and would be bounded by risks calculated for the Road Construction Worker. Consequently, road type and traffic projections are not relevant to the risk assessment and would not need to be accounted for in a specific use request.

Potential doses arising from road maintenance are expected to be on the order of those from the Utility Worker scenario. Full repaving activities would be limited to exposures less than those arising from road construction.

Road maintenance is typically done by milling the surface, cleaning, applying tackifier (to assist in binding new asphalt to the underlying asphalt) and new asphalt, leading to minimal disruption of the road base (the PG containing layer). Section 10.5.3 of IAEA 78 Safety Report Series[15] provides several observations on use of PG for road base and suggests PG roads would require less frequent maintenance as compared to roads constructed with other clay-based and limestone materials.

> *Phosphogypsum has successfully been used as a binder for base course mixtures. Phosphogypsum based mixtures are more workable than clay based mixtures. Delays due to rain during construction are reduced because the compacted mixture does not absorb significant amounts of water. Shrinkage cracks and swelling, which often negatively affect the performance of clay based road beds, are greatly reduced. The stability of compacted phosphogypsum mixtures is superior to that of clay mixtures [186] and there is evidence that the use of phosphogypsum, if correctly optimized, leads to a progressive strengthening of the road bed over time [214, 215].*

Further as regards maintenance to date experience indicates minimal maintenance.

> *In Florida, USA, two experimental roads were built in 1986–1987 using both dihydrate and hemihydrate forms of phosphogypsum [224, 225]. The results of the evaluations are reported in Refs [226–228]. It was concluded that phosphogypsum, when subjected to optimum mixing and compaction, could be transformed into a solid of high strength that is effective as a binder to stabilize on-site soil. Phosphogypsum and sand mixtures, stabilized with a small amount of cement, possessed a load bearing capacity higher than that of locally mined limestone, which was at that time the material of choice for road bases in the region. It was also demonstrated that the incorporation of phosphogypsum into a cement based mixture for making 'roller compacted concrete' (a form of concrete widely used for road construction) led to improved compaction and strength properties [229]. The road bed described in Ref. [224] is shown in Fig. 49, which shows the condition after 25 years of use. The picture was taken during routine resurfacing. While the phosphogypsum is clearly not mixed in fully with other road bed materials, it has, nevertheless, lost none of its load bearing strength. As a result, the only maintenance requirement was a new layer of asphalt.*

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[15] International Atomic Energy Agency (IAEA) 2013. *Radiation protection and management of norm residues in the phosphate*. Vienna. (Safety reports series, ISSN 1020–6450; No. 78) STI/PUB/1582.

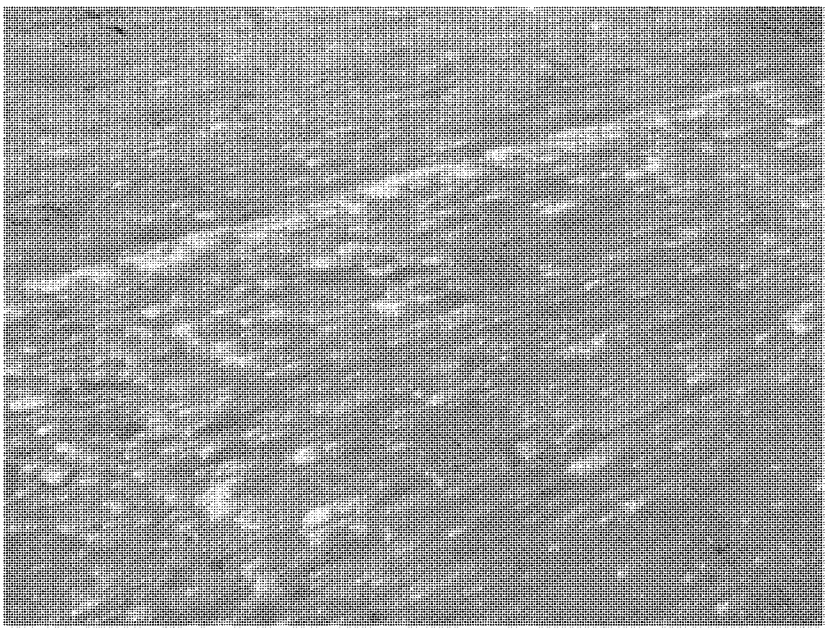

FIG. 49. Experimental road bed in Florida, USA, incorporating phosphogypsum (courtesy: Florida Industrial and Phosphate Research Institute).

In summary, the dose and risk from repairs conceptually cannot be greater than the dose and risk from the original road building since the PG is covered by concrete, asphalt or other material. The Risk Assessment provides the RME scenarios representing categories of exposure conditions with other minor exposure scenario representing lower risks. The example of road maintenance is not considered an RME and requires no further assessment.

Environmental and exposure pathways:

8. USEPA: The risk assessment would benefit from additional analysis of water pathways. Appendix 3 states that "Leaching to groundwater (or surface water) is likely not a complete exposure pathway for the petitioned PG reuse in road construction. This is because roadways are sloped to drain precipitation and paving will act as a barrier to infiltration through the compacted road base beneath. Despite this, literature regarding leaching and water quality was evaluated as part of this screening assessment (see the section titled "Leaching and Water Quality")." (p. 4) At least qualitative consideration should be given to direct contact with surface or groundwater due to flooding events, high water tables, and the presence of karst in phosphate lands. Likewise, reviewers suggested that the risk assessment consider the weathering of the road – will it develop fractures, potentially leading to infiltration resulting from road weathering cause leaching?

Arcadis: Previous risk assessments including 1992 Background Information Document for "Potential Uses of Phosphogypsum and Associated Risks", EPA 1992[16] and SENES 1997[17] examined the potential for impacts to groundwater and surface water pathways. These studies found no realistic potential for impacts to these pathways. Groundwater and surface water pathways were identified to be inconsequential by the EPA BID calculations. Radionuclides were not calculated to reach the nearby well water via the groundwater for almost 10,000 years. For off-site (more distant) wells and river water, radionuclides were not calculated to reach these waterbodies via groundwater for almost 100,000 years. The EPA BID reported in Note C, Table 4.15, that groundwater velocities and retardation factors in the modelling were the factors contributing to this result.

> *No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.*

Exploratory calculations were completed by SENES Consultants Limited (1997) (now Arcadis Canada Inc.) to review how EPA calculations for the Background Information Document (BID) and Final Rule. SENES reconstructed the BID calculations with nearly identical results as shown in Table A.1 from SENES 1997. With respect to water pathways, the results were consistent, showing that there was no impacts or very limited results, orders of magnitude below other pathways of interest, as shown in the table.

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[16] United States Environmental Protection Agency (USEPA) 1992. Potential Uses of Phosphogypsum and Associated Risks, Background Information Document. U.S. Environmental Protection Agency, Air and Radiation (ANR-459). EPA 402-R92-002. May.

[17] SENES Consultants Limited, 1997. Application for Exemption – For Use of PG in the Construction of Thornhill Road, Polk County Florida. Prepared for the Florida Institute of Phosphate Research (FIPR). Draft.

Table A.1

BID RECONSTRUCTION RESULTS
(Asphalt Road Constructed Using Phosphogypsum Containing Radium-226 At 26 pCi/g)

	Comparison of BID results and reconstructed results Dose, mrem per year (Lifetime risk per year of exposure)	
	BID Dose(Risk)	BID Reconstruction Dose(Risk)
Construction Worker		
- gamma no shielding from equipment	41 (1.5×10^{-5})	42 (1.3×10^{-5})
- gamma with shielding from equipment	25 (9.0×10^{-6})	25 (7.6×10^{-6})
- inhalation of dust - dry site	2.5 (2.2×10^{-7})	2.5 (2.1×10^{-7})
- inhalation of dust - humid site	1.0 (8.4×10^{-8})	1.0 (8.6×10^{-8})
Person driving on road		
- gamma	0.22 (8.2×10^{-8})	0.23 (7.2×10^{-8})
Critical Population Group		
- gamma, 100 m off-site	0.043 (1.6×10^{-8})	$<1.0 \times 10^{-7}$ ($<1.0 \times 10^{-13}$)[a]
- ingestion of well water	---[c]	0.0037 (8.2×10^{-10})[b]
- ingestion of food	---[c]	---[b]
Off-site Individual		
- river water from groundwater	---[c]	---[c]
- river water from surface runoff	0.02 (1.5×10^{-8})	0.02 (2.2×10^{-9})

Notes:

a. Critical Population Group gamma dose estimates are less than the stated values. These values were calculated in MicroShield without taking account of shielding provided by the upper layer of road material. Risks for this pathway are calculated based on a risk factor of approximately 3.9×10^{-7} $mrem^{-1}$ (EPA 1989). As MicroShield does not provide radionuclide-specific doses, this alternative approach to the risk calculation was utilized. For further information see Part II, Section 3.3.

b. The values stated for well water ingestion by the CPG correspond to year 10,000. No radionuclides were calculated to reach the well water in any of the prior years that were calculated. The food pathway for the CPG was not modelled as it is expected to have a similar result, or less, than the well water pathway. This is based on the BID assumption that food eaten by the CPG is irrigated with well water.

c. For these pathways, no radionuclides were calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

9. USEPA: Related to the question of whether interactions with ground and surface water are possible, if dissolution or leaching does take place, is there a potential for uptake and bioaccumulation by organisms of any of the radiological constituents of phosphogypsum?

Arcadis: As noted above, radiological groundwater and surface water impacts were not expected to be relevant in the overall risk determinations for this potential use of PG. By extension subsequent

pathways to groundwater and surface water were shown not to be relevant, as documented in BID 1992, Table 4-15 and SENES 1997, summarized in Table A.1 above.

Exposure scenarios/receptors:

10. USEPA: The risk assessment should address the handling of the phosphogypsum between the stack and road construction. The risk assessment should incorporate all handling and processing steps necessary to implement the use. Presumably, pure phosphogypsum would be trucked to a batch plant or other mixing facility, prior to transportation to the construction area. These scenarios should be explicitly considered, including the potential for dust and surface runoff.

Arcadis: Known construction procedures involve PG mixing at the road construction site by placing the PG in the desired location and mixing it into existing or additional soil. Existing calculations consider dust generation at the construction site. These dust intake pathways were found to be orders of magnitude less than external gamma exposure for the construction worker. PG is not batched or mixed prior to use. With respect to loading PG in a truck, the frontend loaders and/or scrapers used to remove PG from a stack to a holding area stockpile at the plant facility for subsequent loading are closed air-conditioned cabs.

Any potential dust exposure to the truck driver or equipment operator is expected to be substantially less in concentration and duration of exposure, compared to the construction worker

For example, as can be seen in the RESRAD output in Appendix C of the Draft Risk Assessment, the annual dose for a road construction worker at the center of the road working on exposed road base, who would experience more direct exposure than a truck driver, inhalation exposure represents 0.5% of the total annual dose. This is presented in the table below.

Road Construction Worker Uranium-238 Dose Exposed to Road Base at Center of Road			
Total Annual Dose (mrem/year)	External Gamma (mrem/year)	Inhalation (mrem/year)	Incidental Ingestion (mrem/year)
28.17	26.11	0.1423	1.918
100.0%	92.7%	0.5%	6.8%

Consequently, the contribution of dust intake for the truck driver or equipment operator is not expected to be relevant to the overall dose and risk calculation.

In addition, consider potential gamma exposures as illustrated by an equipment operator loading the truck using a medium frontend loader. The rate of loading for a 2.25 cubic yards (cy) capacity bucket is 100 cy/hour (Means 2000). Assuming the operator fills ten 20 cy trucks results in an exposure time of two hours per day. In addition, the operator of the front-end loader would be inside a cab located above the PG stack and shielded by the cab. The cab shielding (1 cm of steel) reduces the gamma dose by 50%. This results in the cab operator receiving an annual dose of about 10 % of the construction worker dose (25% exposure duration-2 hours/day and less than 50 % of the gamma dose). The risk is also reduced by at minimum a factor of ten.

11. USEPA: The truck driver scenario only includes direct external exposure from gamma radiation. It should explicitly consider inhalation or ingestion during loading, unloading and truck cleaning.

Arcadis: See comments above. While these additional exposures can be developed, given the discussion in the previous comment, we see no realistic potential for a substantive increase in the calculated risk due to inhalation and ingestion of dust. As described in the response to comment 10, the annual dose for a road construction worker at the center of the road working on exposed road base, who would experience more direct exposure than a truck driver, inhalation exposure represents 0.5% of the total annual dose and ingestion represents 6.8% of the total dose. As a truck driver in the cab of a truck would have less exposure via these routes of exposure than a road construction worker, the relatively small incremental increase in dose has little impact on the resulting risk estimate. Assuming similar percentages for inhalation (0.5%) and incidental ingestion (6.8%) for the truck driver scenario with an annual dose of 18.6 mrem/year, inhalation would be 0.09 mrem/year and ingestion would be 1.27 mrem/year for a total of 20 mrem/year. However, ultimately once converted to risk over a 5-year exposure duration the resulting cancer risk (presented to one significant figure) remains the same (i.e., 20 mrem/year divided by 1,000 mrem/rem, multiplied by the cancer risk coefficient of 5.0×10^{-4} per rem = 5×10^{-5}).

12. USEPA: The utility worker scenario should consider a worker in a trench that parallels the road, rather than crossing it.

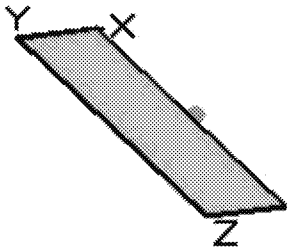
Arcadis: For the Utility Worker Arcadis selected a trench that crosses the road to simply represent an RME scenario, providing a near upper-limit exposure. This scenario provides exposure to an excavated surface on both sides of the worker. The exposure rate as reported in the Risk Assessment is 4.2 µR/hr.

Considering a trench that parallels the road on either side provides only one exposed surface. The result is an exposure rate approximately half (2.15 µR/hr) of the exposure rate arising from the trench considered in the 2019 Risk Assessment. Below are excerpts of a MicroShield output for a trench along the length of the road.

MicroShield Output for Trench Along Length of Road

Source Dimensions	
Length	1.5e+3 cm (49 ft 2.6 in)
Width	1.0e+4 cm (328 ft 1.0 in)
Height	25.0 cm (9.8 in)

Dose Points			
A	X	Y	Z
#1	1.6e+3 cm (51 ft 10.8 in)	25.0 cm (9.8 in)	5.0e+3 cm (164 ft 0.5 in)
#2	1.6e+3 cm (52 ft 10.8 in)	25.0 cm (9.8 in)	5.0e+3 cm (164 ft 0.5 in)
#3	1.6e+3 cm (53 ft 10.8 in)	25.0 cm (9.8 in)	5.0e+3 cm (164 ft 0.5 in)



Shields			
Shield N	Dimension	Material	Density
Source	1.32e+04 ft³	Concrete	2.25
Air Gap		Air	0.00122

Results - Dose Point # 1 - (51.9,8.20e-01,1.64e+02) ft					
Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec	Fluence Rate MeV/cm²/sec	Exposure Rate mR/hr	Exposure Rate mR/hr
		No Buildup	With Buildup	No Buildup	With Buildup
Totals	**1.111e+09**	**5.692e-01**	**1.237e+00**	**9.726e-04**	**2.149e-03**

In the extremely unlikely scenario of a 100 m trench down the center of the road, the resulting exposure rate is estimated by assuming two exposed surfaces results in an exposure rate of 4.3 µR/hr. The incremental length of the trench provides no substantive increase in dose rate due to the extreme angle and distance of the additional exposed surface.

13. USEPA: There may be road user scenarios worth considering, particularly if phosphogypsum may extend beyond the paved areas, e.g., pickup/delivery drivers, workers who mow the shoulders. How would these compare to the currently-modeled scenarios?

Arcadis: As discussed in a previous question, the risk assessment provided an examination of a conceptual road design with risks estimated for scenarios and exposure pathways expected to be the most dominant. The examined exposure scenarios were included in the risk assessment in order to provide the likely maximum scenarios and the scenarios were agreed to by EPA.

The conceptual road design in the risk assessment approximated road design characteristics common in rural, suburban and urban settings and provided plausible exposure scenarios for various types of roads. While larger highway designs could be built, these require larger right-of-way widths of approximately 150 to 300 feet.[18] This leads to larger set-backs for near-by residential housing, resulting in lower dose and risk. Interstate highways typically have restricted access to cyclists and pedestrians, eliminating these

[18] The Federal Highway Administation, Highway History, The Size of the Job, available at https://www.fhwa.dot.gov/infrastructure/50size.cfm

exposure scenarios for large highways. Suburban and urban roads represented a plausible scenario which maximizes exposures for the dominant external gamma pathway.

With respect to pickup/delivery drivers and workers who mow the shoulders the dose assessments for road users provided in the 2019 risk assessment would be bounding and estimate higher doses than doses for other types of road users.

For example, a truck driver may drive 50% of the workday but would likely be on PG road only 25% of the driving hours due to the use of the extensive network of existing roads. Drivers in delivery trucks would also gain the benefit of shielding from the vehicle structure, which is typically a factor of approximately 0.6 (BID 1992). Overall, a scenario with a delivery driver is estimated to result in a dose that is approximately 30% of that estimated for the road user in the 2019 risk assessment.

A worker mowing the grass beside the road may be working for close to a full day but again would likely be beside a PG road only 25% of the driving hours due to the work on the extensive network of existing roads. This worker would also gain the benefit of shielding from the vehicle structure, which is typically a factor of approximately 0.6 (BID 1992). Considering the worker is located beside the road, the exposure to PG is reduced by approximately 50%, as shown in the 1992 risk assessment. Overall, a scenario with a worker mowing grass beside the road is estimated to result in a dose that is approximately 30% of that estimated for the road user in the 2019 risk assessment.

Parameters:

14. USEPA: The worker exposure duration of 5 years is based on both 25% of a 20-year career and of 70% of the project completion time for a major road project (p. 2-9). If the use of phosphogypsum as road base becomes regular practice, would workers not be expected to work on subsequent projects that could also involve phosphogypsum?

Arcadis: The road construction project examples provided in the discussion of this parameter were some of the largest (longest) projects identified. The parameter estimation uses worker statistics and the likelihood of other road construction methods to continue, to estimate a reasonable exposure duration over a construction worker's career.

The Bureau of Labor Statistics employee tenure in 2018 shows that the median years of tenure with current employer for construction industry between 2008-2018 ranges from 3.5 years in January 2008 to 4.3 years in January 2012 (See Table 5 below).

Table 5. Median years of tenure with current employer for employed wage and salary workers by industry, selected years, 2008-2018

Industry	January 2008	January 2010	January 2012	January 2014	January 2016	January 2018
Total, 16 years and over	4.1	4.4	4.6	4.6	4.2	4.2
Private sector	3.6	4.0	4.2	4.1	3.7	3.8
Agriculture and related industries	4.3	4.8	4.1	3.6	4.5	4.6
Nonagricultural industries	3.6	4.0	4.2	4.1	3.7	3.8
Mining, quarrying, and oil and gas extraction	4.1	4.8	3.5	4.0	4.6	5.1
Construction	3.5	4.2	4.3	3.9	4.0	4.1

Burmaster (2000)[19] analyzed employee tenure data from The Bureau of Labor data. The report provides statistical analysis of those data for a wide variety of occupations. For construction in general, the data for men (women not available) show a mean and 95th percentile of 3.23 yr and 12.48 yr. For construction laborer's specifically, the data for men/women show a mean and 95th percentile of 1.74 yr / 1.81 yr and 5.93 yr / 7.08 yr, respectively.

Burmaster (2000) also provides the distributions (in terms of empirical percentiles) for projected duration in years for each occupation type. The table below shows the worker tenure percentile projections for these selected industrial subsectors.

Distribution of Male Worker Tenure by Industry Type

Industry Sector		Percentiles											
	Mean	10	20	30	40	50	60	70	80	90	95	97.5	99
Construction	3.23	0.21	0.45	0.74	1.10	1.54	2.13	2.98	4.39	7.70	12.48	18.24	26.23
Construction Labor	1.74	0.10	0.22	0.36	0.53	0.74	1.01	1.40	2.03	3.45	5.93	11.53	21.26

To be consistent with methodologies to determine RME exposures and risk Arcadis considered that not all construction work will be on PG roads due to possible alternate construction methods and maintenance work for the vast network of existing roads.

The value used in the Risk Assessment represents a portion of industry tenure spent constructing roads: 80% of 25-year worker tenure recommended by USEPA (2014) constructing roads = 20 years; 25% of road construction time spent using PG = 5 years. Based on the employment statistics provide above the actual exposure is likely to be much less than 5 years.

15. USEPA: The TFI Risk Assessment for the Truck Driver scenario uses a density of 1.12 gm/cm3 for phosphogypsum in the truck. U.S. Department of Transportation, Federal Highway Administration, Research and Development Turner-Fairbank Highway Research Center, User Guidelines for Waste and By-Product Material in Pavement Construction, FHWA-RD-97-148 gives a specific gravity range from 2.3 – 2.6 gm/cm3 (p. 19-6), and in a second location states, "specific gravity of solids ranges from 2.30 to 2.50, with an average in the 2.35 to 2.40 range." (p. 19-14). TFI assumes that loose PG in the truck will be about half the density of that identified in the FHWA document. PG that is excavated and loosely placed in a truck will certainly have a higher porosity, but what is the basis for assuming this specific value?

Arcadis: The specific gravity values of 2.3 to 2.6 (unitless) are common in literature about PG. For example, Chang and Mantell 1990[20], reported the average specific gravity values of seven Florida

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[19] Burmaster, David E., 2000, *Distributions of Total Job Tenure for Men and Women in Selected Industries and Occupations in the United States, February 1996*. Risk Analysis, Vol. 20, No. 2, 2000.
[20] Chang, Wen F., and Mantell, Murray I., 1990. Engineering Properties and Construction Applications of Phosphogypsum, University of Miami, Phosphate Research Institute, ISBN No. 87024-328-4.

sources of PG varied between 2.33 and 2.43. The specific gravity values of this magnitude however related to particle specific gravity and ignores the porosity / void space in the bulk material. The same reference reports the maximum dry bulk density of PG following compaction to range between 90.3 to 102.7 lb/ft^3. This compacted bulk density converts to 1.4 to 1.6 g/cm^3. For material excavated and loaded into a truck a swell factor of 20% - 30% is not uncommon for materials such as soil, sand or gravel. For the Risk Assessment the density of the PG in the truck can be supported using a bulk density of 1.4 g/cm^3 with a swell factor of 25% (1.4/1.25) resulting in PG density during transport of approximately 1.12 g/cm^3.

As previously indicated, density is an important factor in assessing potential doses arising from road building. The in-place post compaction density of PG in road base will be specified along with other physical characteristics by the appropriate local, state or federal highway authority. The densities used in the current (2019) risk assessment are considered appropriate for the purpose of risk assessment.

16. USEPA: Assumed inhalation rates may need further justification. As stated in the TFI Appendix 2 (p. 2-11): "The RESRAD default inhalation rate of 8,400 cubic meters per year (m3/yr) was used for the nearby resident receptor. A higher inhalation rate of 11,400 m3/yr was assumed for road construction workers and utility workers. This value was the RESRAD version 6 default for industrial workers and assumes an hourly rate of 1.3 m3/hr." When 11,400 m3/yr is multiplied by the fraction of time spent outdoors (on site) the result is the Road Construction Worker annual inhalation rate of 2,622 m3/yr. This value is about 9% larger than the worker inhalation rate used by the International Commission on Radiation Protection (Guide for the Practical Application of the ICRP Human Respiratory Tract Model, 2002). However, compared to the EPA Exposures Factors Handbook (EPA 2011) Tables 6-1 and 6-28, the inhalation rates for moderate and heavy activities, the RESRAD rate of 1.3 m3/hr is lower than the low end of the range provided for EFH worker inhalation rate. The low end of the range is 1.6 m3/hr and the high end is 4.8 m3/hr, several times higher than the RESRAD rate.

Arcadis: RESRAD exposure parameters for workers were applied where available. Considering the exposure duration of a full day, it is expected that a moderate inhalation rate would be more realistic of the overall inhalation rate as heavy activities would not be continuous throughout the day. The values in Table 6-28 of EPA Exposure Factors Handbook (EPA 2011) ranging from 1.6 m^3/hr for the low end of the moderate activity level, which is for adult females, to 4.8 m^3/hour for the high end of the heavy activity level, which is for adult males, is based on information included in a dated guidance document (i.e., EPA 1985).

More recent studies are referenced in the Exposure Factors Handbook (EPA 2011), several of which were specifically conducted on workers or more specifically construction workers. One study of "high risk" populations exposed to ozone in the Los Angeles area found a mean inhalation rate of 0.78 m^3/hour for healthy adults and a mean of 1.5 m^3/hour for construction workers during a 10-hour work shift (Linn et al. 1992). Linn et al. (1993) studied inhalation rates of construction workers (i.e., laborers, iron workers, and carpenters) during work and break times based on a relationship to heart rate and determined a mean inhalation rate of 1.68 m^3/hour with a standard deviation of ± 0.72. However, estimates of extremes (e.g., 99th percentile) were outside the calibration range of the model and would not be appropriate for an RME. Lastly Allan et al. (2009) determined mean inhalation rates of 1.4 m^3/hour for male construction workers and 1.25 m^3/hour for female construction workers based on probability density distributions generated using Monte Carlo simulation. Therefore, the inhalation rates used which are based on RESRAD defaults are appropriate mean estimates.

While upper percentile estimates may represent a relative extreme, those assumptions are not appropriate for a reasonable maximum exposure scenario. Regardless, using an inhalation rate up to 3 times higher resulting in inhalation doses 3 times higher would still add relatively little to the overall dose and risk as the inhalation route of exposure results in a dose that is orders of magnitude less than external radiation and an order of magnitude or more less than ingestion exposure.

17. USEPA: It is difficult to evaluate the appropriateness of the worker exposure parameters TFI used in Appendix 2, in part due to a lack of detail in discussion of road base and pavement construction process, procedures, and equipment. Page 3-2 states "it was assumed the road construction worker moves around the surface of the road and the direct dose was calculated as the average of the dose at the road center and at the edge of the road." Would different workers have different roles, such as walking directly behind machinery versus walking on the road shoulder? What would happen to the doses if this ratio was changed, such as 75% middle of the road/ 25% edge?

Arcadis: The assumption of the construction worker exposure at both the center of the road and the edge of the road approximates the expected movement of a worker throughout a full workday. Shifting this parameter to the extreme of working 100% of the time in the center of the road would provide a minor increase in the exposure and risk.

As shown in the calculations in a previous question above, assuming the worker spends 100% of the time in the center of the road provides an annual exposure of 28 mrem/yr. This is a 27% increase from the 22 mrem/yr exposure reported in the risk assessment, based on 50% in the middle of the road and 50% along the edge of the road, but makes no change to conclusion that the risk is significantly below 3:10,000. But it is unrealistic to assume a work stands in one spot all day. If a worker did so, he or she would have a very low inhalation rate.

MEMO

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ENVIRONMENT

From:
Douglas Chambers

Date:
April 3, 2020

ARCADIS Project No.:
30006877

Subject:
Responses to Second Set of USEPA Questions - Reclaimer

This memorandum responds to the technical comments and questions to TFI dated March 6, 2020 from the United States Environmental Protection Agency (USEPA). The questions from the USEPA relate to the Reclaimer calculations described in the risk assessment report submitted in October 2019[1] as support to the petition for beneficial use of phosphogypsum. For each paragraph provided by USEPA in their questions, Arcadis has provided a response below.

However, initially, this Response provides the relevant background, the probability of abandoning a road constructed with PG, an assessment of whether the USEPA BID Reclaimer Scenario is a reasonable maximum exposure (RME), and the Hypothetical Reclaimer Scenario in the October 2019 Risk Assessment.

Background

The USEPA BID risk assessment considered a scenario with exposures from gamma radiation and radon over a 70-year period, in which just the road surface is removed, no land preparation is performed, and a house is directly built directly upon PG amended road base material.

The October 2019 Risk Assessment concluded:

> The RME for ultimate disposition of a new road constructed with PG is that it serves as an established part of municipal (county, state and/or federal) infrastructure and as such would require periodic repair and expansion as needed. These activities could include removing the surface, grinding and reusing or disposing of the materials consistent with federal and state and local regulations. Exposures and risks associated with maintenance of roads and reuse of

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[1] Arcadis 2019. *Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum*, Report to The Fertilizer Institute, October.

construction materials are expected to be comparable or less than those detailed in the risk assessment for road construction. It is also noted that as part of road construction, no excess PG is expected to be left over. Road builders avoid transporting extra material to a construction site and would mix in any remaining PG to avoid additional handling.

TFI had Arcadis include a "Reclaimer" scenario in the October 2019 Risk Assessment in the risk assessment in part to document the reasons it was not a RME ultimate disposal option and because USEPA requested that we perform an assessment of the risk for this extreme scenario. It is TFI's understanding that USEPA requested this scenario because it was used by EPA in 1992.

The Probability of Abandoning a Road Constructed with PG

The initial question is, what is the probability of a road constructed with PG will be abandoned.

The Revised Petition includes a summary of the legal framework involved in abandoning a road. This Response include a summary of that legal background to provide context). There are legal, practical, and economic obstacles to abandoning a road.

First, federal regulations govern abandoning a federal road and state transportation laws govern abandoning state and local roads. Since roadways serve a public use (i.e., providing access of citizens of each state to the broader community), these laws, regulations and policies are designed to make it difficult to abandon roads.

Second, roads act as preferential pathways for placement of utilities and other economically important services. Abandoning a road effectively abandons those other societal benefits.

Third, Federal, State, and local roads are sited and maintained to support the federal, state, and local land use requirements. Abandoning a road ignores those broader societal goals.

Finally, the Reclaimer scenario of building a house on top of an abandoned roadway is not consistent with typical land re-use and sustainability policies, is limited by the legal constraints on abandoned public roads, is extremely rare (research has found few, if any, examples. Therefore it is not a reasonably anticipated land use).

Assessing Whether the USEPA BID Reclaimer Scenario Is an RME

The next question is whether the USEPA BID Reclaimer scenario is an RME. The RME is the exposure level utilized in USEPA risk assessments (see the TFI Revised Petition which summarizes the USEPA requirement for using high end, but realistic scenarios).

Even on the face of the 1992 USEPA BID, a 70-year period for the duration of residential exposure is beyond the RME, because the 1992 USEPA BID used 25 years as the duration of a resident's exposure for the nearby resident. Additionally, USEPA's current RME for the duration of residential exposure is 26 years (specifically a 90th percentile of exposure), precisely because "USEPA has been criticized for too

often assuming that future use will be residential" and other unrealistic assumptions.[1] As described above, road abandonment is rare and requires a formal legal process.

In summary, the 1992 BID risk assessment's so called reclaimer scenarios is an extreme scenario well beyond an RME assumption and represents an extreme situation that is unlikely to even occur as described.

The Ultimate Disposition Scenarios Is Repair of the Road

The use of this extreme scenario does not mean it is a RME for ultimate disposition. More realistic situations for the ultimate disposition of the road include continued use of the road as a road, or reuse of the PG road base for a new road, if the road was to be relocated or realigned.

As required by USEPA, the October 2019 Risk Assessment assumed arbitrarily that a road which was constructed is reused for residential purposes, the land preparation activities will realistically result in blending and mixing of the road base to levels that are indistinguishable from background levels.

The October 2019 Risk Assessment, the Response to USEPA's Comments on January 16, 2020, and this Response document that the ultimate disposition is that the road serves as an established part of municipal (county, state and/or federal) infrastructure and as such would require periodic repair and expansion as needed. Below we address disposal of PG road material, if any.

The Hypothetic Reclaimer Scenario in the October 2019 Risk Assessment

To address USEPA's request, therefore, the Petition includes a hypothetical scenario which the risk analysis concludes is an extreme exposure (Extreme Reclaimer), i.e., the exposure is much higher than an RME exposure scenario. That hypothetical scenario assumes a home is built directly on an abandoned PG road, a construction scenario that would likely never occur under existing road construction practices and constraints on future land use for public infrastructure and therefore, the assumed scenario is not an RME scenario (N.B.: Note the distinction between an RME scenario and an individual assumption that is used to calculate the exposure in an RME scenario). The exposure assumptions utilized are more realistic, but high end, assumptions. As discussed above, this scenario does not occur with a sufficient frequency to qualify as a RME scenario, however, the October 2019 Risk Assessment utilized USEPA's 26 years of residence RME assumption (i.e., the 90th percentile). Although this scenario also meets the USEPA risk management limit of 3 in 10,000, it is not an RME and therefore should not represent a condition of approval.

<u>Comment-by-Comment Response</u>

USEPA:

1. One of the key assumptions for the Reclaimer Exposure Scenario identified in the TFI risk assessment, Section 3.4.1 is: *Site grading for construction will almost certainly reduce the*

[1] EPA Land Use in the CERCLA Remedy Selection Process at (OSWER Dir. No. 9344.7-04).

thickness of the layer containing PG; however, for present purposes, we have assumed that site preparation will reduce the PG layer to about 10 centimeters (cm) in thickness and the concentration of Ra-226 in the remaining layer to about 10 pCi/g. No justification is provided for either of these specific values, beyond the risk assessment's description of site grading as a means for reducing the PG layer thickness and concentration. Please provide either a technical justification of how the 10 cm thickness and 10 pCi/g values were derived, or a sensitivity analysis that shows why they are bounding.

Arcadis: As noted above the Reclaimer scenario is an unlikely extreme scenario. Despite this, the scenario was created applying current or future building practices. The Florida Building Code[1] for example requires that slab on grade homes are constructed to certain specifications. Footings are to be supported on undisturbed natural soils or engineered fill. Concrete slab-on-ground floors need to be a minimum 3½ inches (89 mm) thick. The area within the foundation walls under the floor shall have all vegetation, top-soil and foreign material removed. Fill material shall be free of vegetation and foreign material. The fill shall be compacted to ensure uniform support of the slab, and except where approved, the fill depths shall not exceed 24 inches (610 mm) for clean sand or gravel and 8 inches (203 mm) for earth. As a base below the fill material, the building code requires a 4-inch-thick (102 mm) base course consisting of clean graded sand, gravel, crushed stone, crushed concrete or crushed blast-furnace slag meeting specific engineered standards.

These building code requirements are deemed to be reasonable estimates of future requirements for slab-on-grade buildings. In the extremely unlikely event that a Reclaimer home were constructed on an abandoned road, the building code requirements would impose specific actions be taken to prepare the subsurface as described above. In practice, this is expected to eliminate all of the PG road base from beneath the home. Consequently, it is likely the dominant risk pathways associated with the Reclaimer would be eliminated.

For conservativeness and in an effort to respect the USEPA request to examine this scenario, it was assumed that a mixture of the PG in soil was re-introduced into the construction process beneath the floor. Admittedly subjective, the parameters for the PG amended layer and the associated concentration of radium-226, were set at 10 cm and 10 pCi/g which is nearly the maximum radium-226 concentration used for road base in the risk assessment. This estimate is still an extreme assumption, considering the discussion above concerning building code requirements.

USEPA:

2. Arcadis calculates external dose to the reclaimer (due to ground shine through the home foundation) using RESRAD, rather than MicroShield. A foundation thickness of 20 cm was specified in the RESRAD input (Arcadis 2019, pdf page 229), rather than the 10 cm specified on page 3-9. This appears to take credit for a 10 cm granular fill layer that is shown in Arcadis 2019, Figure 3.1, but is not otherwise discussed. Please provide a technical justification for the presence of clean fill.

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[1] 2017 Florida Building Code - Residential, Sixth Edition. (https://codes.iccsafe.org/content/FRC2017)

Arcadis: As noted in the above question and response, the Florida Building Code represents a reasonable set of expectations for future building requirements. For slab-on-grade homes the foundation and sub-floor ground preparation requirements can reasonably be expected to essentially eliminate all the PG road base from beneath the home. Consequently, it is likely the risks associated with the Reclaimer would be eliminated.

If in the extreme case, a mixture of the PG in soil was reintroduced into the construction process beneath the floor, the building code requirements would result in approximately a 10 cm concrete slab supported upon approximately 10 cm of engineered fill.

USEPA:

3. No other reclaimer exposure pathways beyond indoor radon and gamma dose were analyzed, e.g., ground shine from time spent in the yard, inhalation and soil ingestion from working in the garden, consumption of vegetables grown in the garden, consuming water from an onsite well. For example, in addition to radon diffusing through the floor slab, the EPA in 1992 evaluated both of these latter two pathways as potentially contributing to the reclaimer's dose: *The reclaimer is assumed to build a house on the roadbed at some future time after the road is closed and the road surface has crumbled and been removed. In addition to living in a house at the site, the reclaimer drills a well for water and plants a vegetable garden in the contaminated soil. The vegetable garden provides 50 percent of the reclaimer's foodstuffs.* (EPA 1992, page 4-10) The EPA's risk assessment showed these pathways to be minor contributions to the overall dose. If numerical results are not included, these pathways should at least be discussed.

Arcadis: Based on USEPA's request to include the Reclaimer scenario, Arcadis assessed the external gamma and radon pathways. Arcadis focused on the most significant pathways for this scenario.

As indicated by USEPA, the USEPA's 1992 BID[2] demonstrated that almost all of the estimated risk from the hypothetical reclaimer scenario is from external gamma radiation and the inhalation of radon (and its short-lived decay products) indoors. To illustrate, the risks from these two pathways are more than 1,000 times larger than the risks from for example, drinking well water or consuming foods grown in the phosphate amended soils. The exposure pathways other than gamma and radon are for practical purposes trivial and do not require further assessment.

The pathways ground shine from time spent in the yard, inhalation and soil ingestion from working in the garden, consumption of vegetables grown in the garden, consuming water from an onsite well were not considered as their contribution can be considered de minimis. In order to have a yard or a garden topsoil to depth of approximately one foot is typically required to grow grass or vegetables. This negates inhalation and ingestion, reduces ground shine by a factor of close to ten. In addition, most vegetables are shallow root, there will be little radium uptake into the plants. As regards the on-site well, leaching of radium into ground water wells was discounted in the 1992 BID.

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[2] United States Environmental Protection Agency. Potential Uses of Phosphogypsum and Associated Risks – Background Information Document. Air and Radiation (ANR-459), 402-R92-002, May 1992.

From 2019 risk assessment: NCRP 160 also indicates that typical outdoor levels of radon are about 15 Bq/m^3 or 0.4 pCi/L. Thus, the predicted incremental indoor radon level attributable to PG under the home is small by comparison to either the variation in indoor levels or the typical outdoor level of ambient radon.

USEPA:

4. On page 3-10 Arcadis reports an estimated radon flux into the home of .009 pCi/m^2-s. Several parameters were selected which could potentially lead to an underestimate of this value, and some errors are present in the spreadsheet calculation:

   - Radon surface flux is calculated by Arcadis in Figure 3.2. The calculation is performed using a radon diffusion coefficient for the foundation of 4×10^{-4} cm^2/s (from Chauhan and Kumar 2015), and an emanation factor of .062 (Rogers et al 1994 and Chauhan 2015) for intact concrete, and formulas found in US NRC Reg Guide 3.64. The RESRAD default radon diffusion coefficient is an order of magnitude higher, at $3\text{x}10^{-3}$ cm^2/s: *The 3.0×10^{-7} m^2/s default radon diffusion coefficient for the concrete slab is a conservative value compared with the value of 6.0×10^{-9} m^2/s used by the U.S. Nuclear Regulatory Commission (…). It is used to account for possible cracks and other penetrations that may develop in the foundation as the house ages.* (ANL 2001, p. C-12) The RESRAD default emanation factor is .25, half an order of magnitude higher. Using the RESRAD default values results in a radon flux at the surface that is approximately an order of magnitude higher than the value reported by Arcadis. Substituting these low numbers for default values requires additional technical justification.

     Arcadis: There are a number of published values for radon diffusion coefficients. As the reclaimer scenario is not considered to be a (realistically) credible scenario, a detailed evaluation of diffusion coefficients was not performed. However, we point out that Table 7.1 of Yu et. al. 1993[3] provides a review of radon diffusion coefficients. The value of 4×10^{-4} cm^2/s is central to the values reported by Yu et. al. (1993) and considered suitable for the screening analysis provided in the current risk assessment.

     There are considerable data on the emanation coefficient of 0.062 used in the current assessment (as captured in the radon flux calculations) and is in the range of published emanation coefficients. The emanation factor of 0.062 used in this assessment is from a paper

[3] ANUEAIS-8 Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil by C. Yu, C. Loureiro,* J.-J. Cheng, L.G. Jones, Y.Y. Wang, Y.P. Chia,* and E. Faillace, Environmental Assessment and Information Sciences Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439.

by Vern Rogers[4], specific to concrete in Florida construction (experimentally determined) and in our view appropriate.

- In the spreadsheet provided by Arcadis, the term $\sqrt{a_b/a_f}$ from Reg Guide 3.64 Equation 12 was not included. By disregarding this term, Arcadis' calculation does not account for differences between the porosity, radon diffusion coefficient, and moisture content of the foundation and underlying layers.

  Arcadis: There are no terms in equation 12 "a_b" or "ar". It is assumed the terms cited should be "ai" and "a_c" the interface coefficients. As the basis for this case assumed approximately the same diffusion coefficient, porosity and moisture saturation fraction, the ratio is unity and this term can be ignored in the multiplication. Additionally , the screening analysis considered the effect of this factor which as USEPA notes is intended to adjust for the differences in media (a sort of "transition from one media to another) to be inconsequential and on the order of about 10% (and in any event if incorporated, would reduce the radon flux and not increase it).

- The spreadsheet contains an error. Cell 'Diffi Co 2 unit conc (2)'!F46:F55 does not correctly multiply all correct parts of the term by the exponential.

  Arcadis has checked this calculation and appreciates the identification of a missing bracket. We have made a modification to the spreadsheet to show the impact of this change. The revised spreadsheet is attached. The overall dose including external gamma is updated to be 4 mrem/yr as opposed to 3 mrem/yr. In total the dose for 26 years of exposure results in 104 mrem or a risk of 0.5 in 10,000.

- Rather than calculate the buildup of radon daughter products within the home, the TFI risk assumed an equilibrium factor of 0.4. This may be a reasonable assumption, but was not well documented and may explain some of the difference in indoor radon dose between TFI's risk assessment and EPA's 1992 risk assessment.

  Arcadis: The 0.4 indoor equilibrium factor is a widely used default (notional value) for such calculations and is considered suitable for such generic risk calculations as postulated for the hypothetical and extremely unlikely reclaimer scenario[5].

The most consequential of these issues is the calculated radon flux through the foundation. Using more conservative, and arguably more realistic, estimates of the emanation factor and radon diffusion coefficients, the radon air concentration in the home could be several orders of magnitude higher than the 0.013 pCi/L (13 pCi/m^3) reported by Arcadis, and the reclaimer's inhalation dose more than an order of magnitude higher than the 1.8 mrem/yr reported for the reclaimer. The conceptual treatment of the

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[4] Rogers V., Nielson K., Lehto M., Rodger H. Radon Generation and Transport Through Concrete Foundations. United States Environmental Protection Agency, Air and Energy Engineering Research Laboratory, EPA/600/SR-94/175. November 1994.

[5] NCRP 160, or UNSCEAR 2008 Annex E

slab and sub slab should generally be better explained. As stated above, the treatment of indoor radon for the reclaimer should be thoroughly justified wherever it departs from model default values and/or USEPA's 1992 risk assessment.

Arcadis: Further discussion of the basis for the assumed characteristics of the slab-on-grade home postulated for the hypothetical reclaimer is provided earlier in the memorandum and is based on Florida Building Code guidance as previously indicated.

As previously indicated, we suggest that the assumptions and model parameters used in the risk assessment are appropriate for the screening analysis of a reclaimer scenario.

As an aside, the average indoor radon level in US homes is about 1.4 pCi/L and the average (notional perhaps) outdoor level of radon is about 0.4 pCi/L. Thus, while we consider the calculations performed to be reasonable, even if the predicted indoor radon levels were to increase by a factor of say 10 to 0.013 pCi/L, the incremental levels would be in the variability of natural back indoor levels and for that matter within the natural variability of natural background radon levels outdoors.[6]

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[6] United Stated Environmental Protection Agency. A Citizen's Guide to Radon. EPA402/K-12/002|2016|www.epa.gov/radon

THE FERTILIZER INSTITUTE

Supplement to The October 11, 2019 TFI Phosphogypsum Reuse Petition: 2019 Radium-226 Results for U.S. Phosphogypsum Stacks

December 5, 2019

I. INTRODUCTION

On October 11, 2019, The Fertilizer Institute ("TFI") submitted a petition (hereinafter, the "Petition") to the U.S. Environmental Protection Agency ("EPA") requesting approval for the beneficial use of phosphogypsum ("PG") in road construction (*i.e.*, road base and/or concrete pavement), provided the PG contains no more than an average radioactivity concentration of 35 picocuries per gram ("pCi/g") of Radium-226 ("Ra-226").[1]

In conjunction with the submission of the Petition, TFI members agreed to perform radiological testing of PG. In particular, at EPA's request, two TFI members utilized EPA EML HASL-300 Method Ga-01-R (a 21-day method), entitled "Gamma Radioassay,"[2] for the sampling event. These members' PG stacks are located in Central Florida (where the highest Ra-226 levels would be expected), Louisiana, and the Western U.S. Because Northern Florida PG is used as a soil amendment and is regularly tested for Ra-226 using a different EPA-approved method, it is not included in this discussion.[3]

II. 2019 PG SAMPLING PROGRAM AND RESULTS

Nine stacks located in four states were tested. Ten samples were taken from each stack, for a total of 90 samples.[4] A summary of the results is as follows:

- The average Ra-226 concentration of all 90 samples is 18.6 pCi/g.
- Ra-226 concentrations in individual samples range from 6.3 pCi/g to 27.9 pCi/g.
- The average concentration in the Western U.S. is 15.8 pCi/g.
- As expected, the highest average PG stack result is from Central Florida (24.7 pCi/g), with the average of all six Central Florida stacks being 19.6 pCi/g.

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[1] This level was proposed first and foremost with public safety in mind. The risk assessment analysis provided with the Petition demonstrates that PG containing Ra-226 levels up to 148 pCi/g is safe for road construction (*i.e.*, this concentration corresponds to EPA's regulatory risk of 3 in 10,000). *See* Arcadis, Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum at 5-2 (Oct. 2019) (hereinafter, the "Risk Assessment"). Further, an average Ra-226 concentration of 35 pCi/g represents the high-end of expected levels of Ra-226 in U.S. PG stacks (as discussed in Section III.B, below). PG containing <10 pCi/g has been used as an agricultural amendment for many years. This PG use is not the subject of the Petition.

[2] This method provides conservative Ra-226 values, reported by the laboratory as "Bismuth-214 (Ra-226)."

[3] PG used for agriculture purposes is tested for Ra-226 using EPA Method 903.1, entitled "Radium-226 in Drinking Water Radon Emanation Technique." Although a comparison cannot be made between the current sampling program and 2019 results from the three Northern Florida PG stacks tested using Method 903.1, for reference, the average 2019 sampling results for these three stacks (representing 30 samples) is 6.47 pCi/g.

[4] To preserve confidentiality, the results from the 2019 sampling program were blinded so the identity of the company and stack location were not disclosed.

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Table 1 sets forth results from the 2019 sampling program. The values highlighted in yellow are the highest test result for each stack, and the values highlighted in green are the lowest results. The average and median values are also provided for each stack.

Table 1 – Aggregate PG Ra-226 Data from September 2019 (Reported as pCi/g)

	Central Florida						Louisiana	Western U.S.	
Sample No.	**Stack 1**	**Stack 2**	**Stack 3**	**Stack 4**	**Stack 5**	**Stack 6**	**Stack 7**	**Stack 8**	**Stack 9**
1	23.3	24.9	16.6	19.9	27.9	19.2	19.8	24.2	8.51
2	27.0	24.5	17.3	9.0	17.7	7.23	18.9	24.3	8.38
3	16.1	25.4	17.5	25.8	23.8	17.1	16.2	22.3	7.82
4	24.1	26.6	19.3	20.3	22.4	27.2	15.9	21.3	6.83
5	18.9	24.2	10.3	21.6	14.6	24.8	16.1	25.5	6.32
6	21.7	20.6	18.6	19.5	17.7	19.1	21.9	24.8	8.17
7	21.4	24.2	10.4	24.7	18.2	21.4	16.7	25.1	7.37
8	25.0	25.6	11.0	18.5	18.9	12.6	19.2	25.3	6.88
9	19.5	27.8	13.8	17.1	23.8	7.27	18.7	25.2	6.80
10	14.9	23.1	15.3	22.7	16.6	13.3	17.9	24.3	7.50
Average	21.19	24.69	15.01	19.91	20.16	16.92	18.13	24.23	7.46
Median	21.55	24.70	15.95	20.10	18.55	18.10	18.30	24.55	7.44

III. ANALYSIS OF THE 2019 PG SAMPLING RESULTS

A. Comparison of the 2019 Results to The Risk Assessment Included With The Petition

The data provided above assist in the assessment of regulatory risks. The Risk Assessment submitted in support of the Petition demonstrates that PG containing an average of 148 pCi/g corresponds to the EPA safe Ra-226 risk goal of 3 in 10,000 (see Table 2 below, reprinted from the risk assessment submitted as part of the Petition).[5]

Table 2 – Radionuclide Risk Assessment from the Petition

Average Ra-226 in PG*** (pCi/g)	Exposure Duration Dose (Mrem)	Risk
10	40.7	0.20 per 10,000
20	81.5	0.41 per 10,000
27	110	0.55 per 10,000
30	122	0.61 per 10,000
35	143	0.71 per 10,000
40	163	0.81 per 10,000
50	204	1.02 per 10,000

*** Although we are not aware of any PG with average Ra-226 concentrations anywhere near 148 pCi/g, such PG could in principle be used for road construction and still achieve the EPA's safe level of a risk of 3 in 10,000.

[5] Risk Assessment at 5-2 (Table 5-1).

When viewed in light of the risk assessment, the 2019 PG sampling results demonstrate that the use of PG in the proposed application is consistent with EPA's view of a safe level of risk. For example:

- The average Ra-226 concentration from the 2019 stack sampling (18.6 pCi/g) is below the radioactivity concentration limit of 35 pCi/g proposed in the Petition, and well below the average Ra-226 concentration of 148 pCi/g that corresponds to an EPA safe risk level of 3 in 10,000.

- No individual concentration from the 2019 stack sampling (with concentrations ranging from 6.32 pCi/g to 27.9 pCi/g) exceeds 35 pCi/g.

- The average concentration of the six Central Florida PG stacks (19.6 pCi/g) as well as the individual PG stack averages (ranging from 15.01 to 24.69 pCi/g) are below the radioactivity concentration limit of 35 pCi/g proposed in the Petition, and well below the average Ra-226 concentration of 148 pCi/g that corresponds to an EPA safe risk level of 3 in 10,000.

- The average concentration in the Western U.S. (15.8 pCi/g) is below the radioactivity concentration limit of 35 pCi/g proposed in the Petition, and well below the average Ra-226 concentration of 148 pCi/g that corresponds to an EPA safe risk level of 3 in 10,000.

Thus, the 2019 sampling results demonstrate that the average of all 2019 stack samples and every individual sample result are well below the proposed radioactivity concentration limit of 35 pCi/g, and significantly below EPA's safe risk level of 148 pCi/g set forth in the Petition.

B. Comparison to Prior EPA PG Results

For context, in a 1992 Background Document,[6] EPA summarized data from a 1988 sampling of Central Florida PG stacks. The information from EPA's Background Document is reprinted below.

Table 3 – Reprint of EPA 1988 Central Florida PG Ra-226 Sampling Results

Phosphogypsum Stack	Mean Concentration (pCi/g dry)*	Concentration Range (pCi/g dry)
Gardinier	33± 2	31-37
W. R. Grace	30 ± 9	19-48
Royster	30 ± 11	16-49
Conserve	34 ± 18	23-81
Estech	25 ± 4	19-31

*Mean concentration with the standard deviation of samples from 10 locations on each stack.

Although the method of analysis from the 1988 sampling effort is unknown, the mean (average) results (ranging from 25 to 34 pCi/g) are higher than the average results from the 2019 sampling of Central Florida PG stacks (ranging from 15.01 to 24.69 pCi/g). However, both the 1988 and 2019 sampling results from Central Florida PG stacks demonstrate that the average concentrations are all below 35 pCi/g (the limit proposed in the Petition), and significantly below 148 pCi/g (the Ra-226 concentration corresponding to a 3 in 10,000 risk level).

[6] EPA, Potential Uses of Phosphogypsum and Associated Risk, Background Information Document, 402-R92-002 at 2-7 (Table 2-4) (May 1992).

C. Comparison to International PG Sampling Results

In addition to the 2019 and prior EPA sampling of U.S. PG stacks, data exist on the average Ra-226 concentrations in PG from 23 countries (including other data from U.S. stacks) that further confirm the 2019 U.S. PG stack data. According to published PG stack data, the Ra-226 concentrations range from 1 pCi/g (35 Bq/kg) to 38.4 pCi/g (1,420 Bq/kg)).[7] Representative information from the international review of PG Ra-226 data is set forth in Table 4.

Table 4 – NORM Radionuclide Activity in Phosphogypsum

Country	Ra-226 Concentration in becquerel/kilogram (Bq/kg) (converted to pCi/g)	Number of Samples	Reference
Australia	246 (6.7 pCi/g)	28	Beretka and Matthew (1985) Cooper (2005 and Msila et al. (2016)
Brazil	410 (11.1pCi/g)	268	De Conceicao and Bonotto (2006); Mazzilli and Saucia (1999) Santos (2006) Xhixha et al (2013)
Germany	305 (8.2 pCi/g)	2*	Trevisi et al. (2012)
Greece	440 (11.9 pCi/g)	31	Trevisi et al. (2012) and Turhan (2008)
Israel	747 (20.2 pCi/g)	1*	Gezer et al. (2012)
Jordan	378 (10.2 pCi/g)	16	Al-Jundi et al. (2008) Gezer et al. (2012)
Korea	618 (16.7 pCi/g)	1*	Gezer et al. (2012)
Morocco	1420 (38.4 pCi/g)	1*	Xhisha et al. (2013)
Spain	491 (13.3 pCi/g)	91	Trevisii et al. (2012)
The United Kingdom	1020 (27.6 pCi/g)	91	Trevisi et al. (2012)
United States	750 (20.3 pCi/g)	95	Hull and Brunett (1996); Roper et al. (2013)

* Sample too small to be statistically significant.

Even though the analytical methods used in the international compilation are not known, the average for the U.S. (20.3 pCi/g) corresponds closely with the 18.6 pCi/g average concentration across all nine stacks from the 2019 sampling program. These data (as well as the 2019 TFI data and the 1988 EPA PG data) illustrate

[7] See Chapter 6 at Table 6.16 in "Naturally Occurring Radioactive Materials in Construction" (2017). Chapter 6: "From raw materials to NORM by-products" is authored by T. Kovacs, et al., and is available from ScienceDirect, at https://www.sciencedirect.com/book/9780081020098/naturally-occurring-radioactive-materials-in-construction). Section 6.6.1.2 Radiological properties from Naturally Occurring Radioactive Materials in Construction, which contains Table 6.16, is also available online at https://www.sciencedirect.com/topics/engineering/phosphogypsum).

that the variation of individual Ra-226 concentrations in PG is relatively low, particularly compared to the safe level of 148 pCi/g.

All of the data support the view that it is very unlikely that any PG in U.S. stacks will exceed either (1) 148 pCi/g (EPA's PG safe level), or (2) 35 pCi/g (the level proposed in the Petition for reuse). Thus, no sampling should be required prior to shipping PG for road construction uses.

IV. CONCLUSION

Key highlights from this Supplement to TFI's Petition are set forth below:

- As expected, the highest levels of naturally occurring radiation are associated with the Central Florida samples.
- All of the data demonstrate that the individual, average, and medium Ra-226 concentrations from U.S. PG are below 35 pCi/g, and well below the 148 pCi/g level corresponding to EPA's safe level of 3 in 10,000.

These results verify that the Petition contains a reasonable maximum limit for the beneficial use of PG in U.S. road construction.

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Economic Analysis of Phosphogypsum reuse

The Fertilizer Institute

Submitted by:

Policy Navigation Group

December 2019

EXECUTIVE SUMMARY

Policy Navigation Group (PNG) conducted this analysis on behalf of The Fertilizer Institute (TFI) to estimate the potential regulatory cost savings of changes that would expand the use of phosphogypsum (PG) to include road construction. This application is in use in Europe and elsewhere, but currently is precluded in the U.S. due to U.S. Environmental Protection Agency (EPA) regulatory restrictions. This section outlines the main steps we undertook to perform the analysis and summarizes the economic benefits of using PG for road construction.

Outline of Steps in Analysis

In the analysis that follows, we take these steps to estimate the potential cost savings of using PG for road construction:

> **Identify the costs to manage PG currently in stacks located at numerous sites.** These include the costs of land for the stacks, the costs to transport PG to the stacks, the costs of managing water at and preserving the physical stability of the stacks, and the costs to close the stacks.
>
> **Assess scenarios for PG reuse in road construction in the near future.** We assume that PG reuse will start modestly and grow over time. Given market uncertainty over the potential demand for PG, we estimate the savings for a lower-bound and an upper-bound scenario; any savings are expected to be within this range. Due to transportation costs and the availability of substitutes, we assume that the PG reuse market faces natural limits and largely is confined to locations relatively close to current plants and stacks.
>
> **Estimate the cost savings from PG reuse.** Companies can incur savings in PG management costs if they send PG to be reused (stack management savings from the regulatory reform). Since the stack management savings from the regulatory reform frees up the labor, capital, and physical land needed for PG stack management, in competitive markets some of these savings are passed through to the companies' customers and purchasers of PG for reuse. Ultimately the savings pass through to the state and local highway departments, companies' shareholders, companies' workers, farmers and other purchasers of fertilizer, and other households and firms.[1] For this reason, these cost savings are also the social benefits of the reform. They are also the deregulatory savings from an EPA action to allow reuse for road construction.

Figure ES-1 summarizes the key inputs used in the analysis and shows the data transformation and resulting outputs.

---

[1] In this analysis, we only consider the direct economic impact of the reform. There will be indirect and induced economic impact of the reform as fertilizer customers have lower input costs and can gain market share from imports and as workers spend their greater compensation on consumer goods and services. These gains then induce additional economic impact such as higher spending by vendors to the fertilizer purchaser and the workers.

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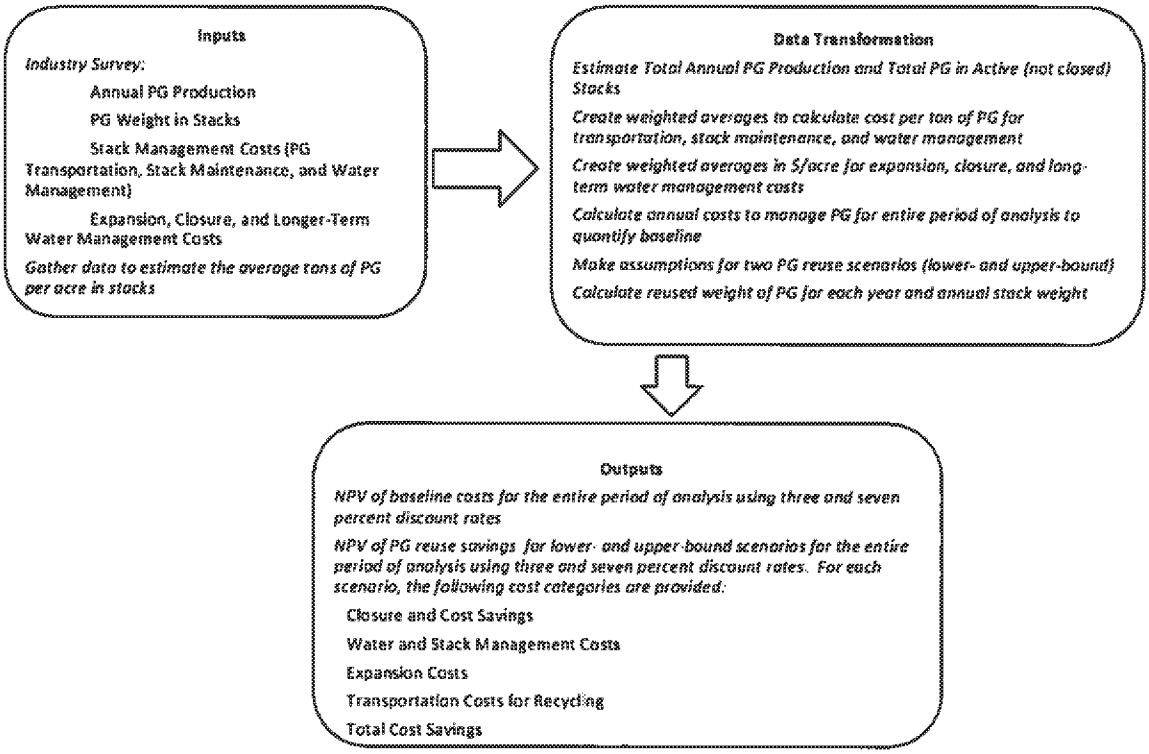
Figure ES-1: Diagram Summarizing Analytical Approach for Project[2]



Summary of the Regulatory Savings

The analysis produced by taking the steps above provides a clear picture of the cost savings of using PG for road construction. Table ES-1 presents the baseline costs to manage PG from 2020-2042, which range from $1.3 billion to $0.88 billion using three and seven percent annual discount rates. Table ES-2 summarizes the cost savings from PG reuse for the two reuse scenarios; it shows that the total net present value (NPV) savings range from $37 million to $52 million for the lower-bound scenario and from $110 million to $160 million for the upper-bound scenario, using discount rates of seven and three percent, respectively.[3] We use three and seven percent discount rates to calculate the results from this analysis, as directed by U.S. Office of Management and Budget Circular A-4.

[2] We use three and seven percent discount rates to calculate the results from this analysis, as directed by the U.S. Office of Management and Budget's Circular A-4.

[3] The results presented in this analysis are rounded to two significant figures. Due to rounding, total values in the tables may not sum.

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Table ES-1: Net Present Value (NPV) of Baseline Costs to Manage PG

CATEGORY	NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)
Baseline Costs	1,300	880

Table ES-2: Net Present Value (NPV) of Cost Savings from PG Reuse

COST CATEGORY[4]	LOWER-BOUND SCENARIO NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	LOWER-BOUND SCENARIO NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)	UPPER-BOUND SCENARIO NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	UPPER-BOUND SCENARIO NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)
Closure Cost Savings	11	11	33	32
Water and Stack Management Costs	22	13	65	37
Expansion Costs	19	13	57	38
Total Cost Savings	52	37	160	110

In summary, expanding the use of PG in road construction is expected to result in savings not only to PG producers, but also to numerous users of PG and workers, shareholders, and customers of fertilizer firms.[5]

[4] Transportation savings are omitted from the results shown in this table as they amount to zero dollars. Transportation cost from the stack to the construction site is not included because it is assumed that the customer would pay for this transportation as part of the road construction cost.

[5] Savings to users of PG, workers, shareholders, and customers of fertilizer firms are not evaluated in this economic analysis.

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INTRODUCTION

Policy Navigation Group (PNG) conducted this analysis on behalf of The Fertilizer Institute (TFI) to estimate the potential regulatory cost savings of using phosphogypsum (PG) for road construction, an application currently in use in Europe and elsewhere. This section provides a summary of the industry, followed by a description of PG, its production in the U.S., and U.S. Environmental Protection Agency (EPA) PG requirements. It then touches upon PG reuse options and scenarios before concluding with a description of how the remainder of the report is organized.

Summary of Industry

Phosphate rock is predominantly used to produce phosphoric acid, which is primarily used to manufacture fertilizer. The U.S. was previously the largest producer of phosphate rock and leading exporter of phosphate fertilizer, until China increased its production in 2011 and surpassed the U.S. as lead world exporter in 2014.[6] Currently, the U.S. is the second-largest consumer of phosphate rock (consuming 29 million metric tons (MT)) and the second-largest producer of phosphoric acid (producing 14 million MT).[7] Domestically, phosphate rock ore is mined primarily by five firms in four states — with 80 percent of the mining occurring in Florida and North Carolina — to produce approximately 27.1 million tons of marketable product.[8] After being mined in open-pit mines, phosphate rocks are treated, washed, and dried in rotary kilns.[9] The ore is then finely ground and converted into a soluble form through either a wet or dry process. In the U.S., facilities exclusively use a wet process that digests the phosphate rock in a reaction vessel with sulfuric acid, producing both phosphoric acid and a largely calcium sulfate byproduct known as PG.

Total worldwide production of PG is estimated between 100-280 mega tons per year.[10] About 85 percent of world PG production is discarded or stored. The remaining 15 percent of worldwide production is reused as soil amendment, agricultural fertilizer, and set controller for cement and building materials worldwide.

Around the world, PG is used in a range of applications, including:[11]

- In fertilizer for agricultural soils;
- In backfill and road-base material for roadway and parking lot construction;
- As an additive to concrete and concrete blocks;

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[6] Jasinski, "Phosphate Rock."

[7] European Phosphate Fertilizer Alliance, "Data and Statistics: Phosphoric Acid."

[8] Jasinski, "Phosphate Rock."

[9] U.S. Environmental Protection Agency, "Potential Uses of Phosphogypsum and Associated Risks: Background Information Document for 40 CFR 61, Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks."

[10] Sahu et al., "Natural Radioactivity Assessment of a Phosphate Fertilizer Plant Area."

[11] U.S. Environmental Protection Agency, "Potential Uses of Phosphogypsum and Associated Risks: Background Information Document for 40 CFR 61, Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks."

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- In wallboards;
- In mine reclamation; and
- In the recovery of sulfur.

Prior to the 1992 EPA restrictions on its widespread reuse, PG was critical to the peanut industry as a soil amendment valued for its fertilizer properties across Georgia, North Carolina, Virginia, and Alabama, and on farms across the southeast that grow tobacco, corn, small grain, and sugar cane.[12] As a large peanut producer, Georgia was the largest PG consumer. States such as California also used PG for soils growing citrus, almonds, vegetables, and tomatoes. In these and other locations, PG was widely used, since it had been shown to be a beneficial source of sulfur in improving crop yields.

Description of Phosphogypsum

PG byproduct is filtered from the phosphoric acid and transferred as a water slurry to be stored in open-air areas called PG stacks. The slurry is pumped atop the stack, where an engineered "gypsum stack and pond" is formed. Water impounded from PG stacks is reused in the overall wetting process. Closing PG stacks involves complex engineering, including placing high-density polyethylene liners as caps to prevent rainwater from infiltrating and reduce stack water from percolating out from the bottom of the stacks.[13]

Reuse Options and Scenarios

Other countries, most notably Japan and some nations in Europe, have and currently reuse some PG for specified uses that have included road base material, cement, wallboard, and other building materials.[14]

Road Base

Prior to EPA restrictions on its use in 1992, PG was mixed with ash, sand, gravel, or cement, and was used as a base for roads, parking lots, and storage areas to help control setting times, counteract shrinkages, strengthen cement products, and create resistance to sulfate etching.[15] Numerous publications are available detailing these uses. The following are some examples of how PG was used in Texas, Florida, and North Carolina:[16]

- In Pasadena, Texas, PG was mixed with fly ash and cement for road base at five sections of city streets in La Porte, Texas.
- In Polk County, Florida, PG was mixed with granular sand to construct 2.4 kilometers of road base, surfaced with asphalt.

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[12] U.S. Environmental Protection Agency.

[13] BCI Engineers & Scientists, Inc., "Phosphogypsum Stack Closure: Evaluation of Phosphogypsum as an Alternate Final Cover."

[14] U.S. Environmental Protection Agency, "Potential Uses of Phosphogypsum and Associated Risks: Background Information Document for 40 CFR 61, Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks."

[15] U.S. Environmental Protection Agency.

[16] U.S. Environmental Protection Agency.

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- In Columbia County, Florida, two miles of road base was constructed with 100 percent dehydrated PG and varying mix ratios of PG and sand. The road base was also surfaced with asphalt.
- In North Carolina, PG was commercially used as a fill and sub-base for roads in swampy areas.
- In Bartow, Florida, the Florida Institute of Phosphate Research used a mixture of PG and concrete to pave two thousand yards of driveway and parking areas.

Cement and Concrete Aggregate

PG also has been used to manufacture building materials, including concrete and cement aggregates, particularly outside the U.S.[17] Additionally, it can be used more extensively in building materials, including cement, wallboard, ferrocement panels, plasterboard panels, partition blocks, plaster, tiles, artificial stone, and glass ceramics.[18]

Several studies have demonstrated that PG can help prolong concrete setting times.[19] The increased setting time supports long-term concrete strength. Incremental initial and final setting times increase with increasing PG content. Using PG as a retarder agent is particularly beneficial in civil engineering work involving casting in hot weather, casting retaining deep walls, and casting mass concrete and repair elements, for example.[20]

Including PG in cement also has the benefit of reducing density, increasing chemical resistance, increasing free resistance, and increasing fire resistance.[21] As such, PG has the potential to be used as a partial substitute for materials aggregate in concrete.

Organization of the Report

The rest of the report discusses current PG management costs and incurred savings from PG reuse, showing how we developed scenarios for PG reuse and estimated the cost savings for these scenarios. Since the regulatory change frees up the labor, capital, and physical land needed for PG stack management, these savings are also the social benefits of the regulatory reform.

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[17] U.S. Environmental Protection Agency.

[18] Rashad, "Phosphogypsum as a Construction Material."

[19] Rashad; Shen et al., "Calcium Sulphoaluminate Cements Made with Phosphogypsum: Production Issues and Material Properties"; Singh, "Treating Waste Phosphogypsum for Cement and Plaster Manufacture"; Altun and Sert, "Utilization of Weathered Phosphogypsum as a Set Retarder in Portland Cement."

[20] Rashad, "Phosphogypsum as a Construction Material."

[21] Rashad.

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CURRENT PG MANAGEMENT COSTS AND COST SAVINGS FROM PG REUSE

Introduction and Methodology Overview

This section provides an overview of current PG production and PG stored in stacks; details and quantifies the current costs of PG management; describes and quantifies the potential short- and long-term cost savings if a percentage of currently produced PG is reused for road construction; provides baseline and PG reuse scenarios to illustrate several key points; and presents the variables, assumptions, and methodology used in all the above.

A survey was conducted with members of TFI in July 2019. The survey included questions on current PG production; weight of PG stored in active stacks; and costs to transport, manage, expand, and close stacks. The survey was conducted, compiled and summarized by an independent party who removed identifying information before data was provided to PNG for analysis. The survey questions are provided in Appendix 1.

Using the survey information, we estimate averages for current production, average weight of PG stored in active stacks, and costs. With these estimates, we calculate the current costs of managing PG — the baseline costs. Then, we create two scenarios (lower- and upper-bound) to estimate the cost savings if a percentage of the PG produced is beneficially reused.

The timeline of the analysis is from 2020 to 2042. All future values are discounted using a three and seven percent discount rate and presented in 2019 dollars.[22] The values in the tables are rounded to two significant digits. Therefore, the totals shown in some tables may not sum exactly. We only consider active PG stacks for this analysis, as according to information received from the industry, it is unlikely that PG from closed stacks would enter the reuse market.

PG Production and Annual Growth Rate

Survey participants provided annual PG production data (in tons per year) for 2016, 2017, and 2018 for nine active stacks. Data was provided by the largest PG producers in the U.S., but it does not include all active stacks and PG producers in the country. To account for variability across stack data (both, on annual basis and by stack), we calculate weighted averages. To calculate the weighted annual production rate, we estimate the average growth (in tons) for each stack from 2016 to 2017 and from 2017 to 2018. Then, we estimate the corresponding weighted average growth rate for each period (from 2016 to 2017 and 2017 to 2018). We derive industry representative weighted averages by weighing each stack's size by its proportion of the sum of the size for all the stacks in the survey.

To estimate the annual production of PG available for reuse, we calculate the weighted average across all the active stacks. For this estimate, we quantify the multi-year average per active stack (from 2016 to 2018) and then the weight of the multi-year average per stack in relation to all the active stacks. This gives a weighted average annual production of PG of 5.1

[22] U.S. Department of Labor, Bureau of Labor Statistics, "CPI Inflation Calculator."

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million tons. We multiply this value by nine stacks to obtain a weighted annual total U.S. production of 46 million tons of PG.

For this report, we assume that PG production in the U.S. will not experience growth in the timeline of the analysis — that it will remain at the same level as in the baseline. We make this assumption because information received from the industry for this analysis forecasts no growth. Furthermore, the survey data spans only a three-year period and varies by company and year, rendering it difficult to determine any long-term trend in terms of growth. We note that this assumption is in line with market reports from Europe, which show near-zero growth for PG production between 2012 and 2017.[23]

Table 1 summarizes the PG production data used for the analysis.

Table 1: PG Production

ITEM	AMOUNT
Weighted Average of Production, Per Year, Per Stack	5,100,000 tons
Total Annual Production of PG	46,000,000 tons

PG Stored in Stacks

For the nine active stacks discussed in the previous subsection, we received the approximate amount of PG stored in each. For eight of the nine stacks, the weight was provided in tons. For one of the stacks, we were provided the volume in cubic yards, which we converted into tons using a density factor of 1.9 tons per cubic yard.[24]

The surveyed companies also provided information for inactive stacks, as PG from inactive stacks may be used.

Using the survey information, we add the total weight in both active and inactive stacks. Additionally, we calculate the weighted average tons for both types of stacks by creating weights per stack (that is, how much each stack represents of the total in the corresponding category). These weights are further used to estimate the average costs per ton (see subsection below).

[23] Layr and Hartlieb, "Market Analysis for Urban Mining of Phosphogypsum."

[24] City of Moorpark, "Construction Demolition Conversion Table." This value comes from a conversion factor for gypsum used in drywall.

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Figure 1: Projected New PG Production and PG in Stacks[25]

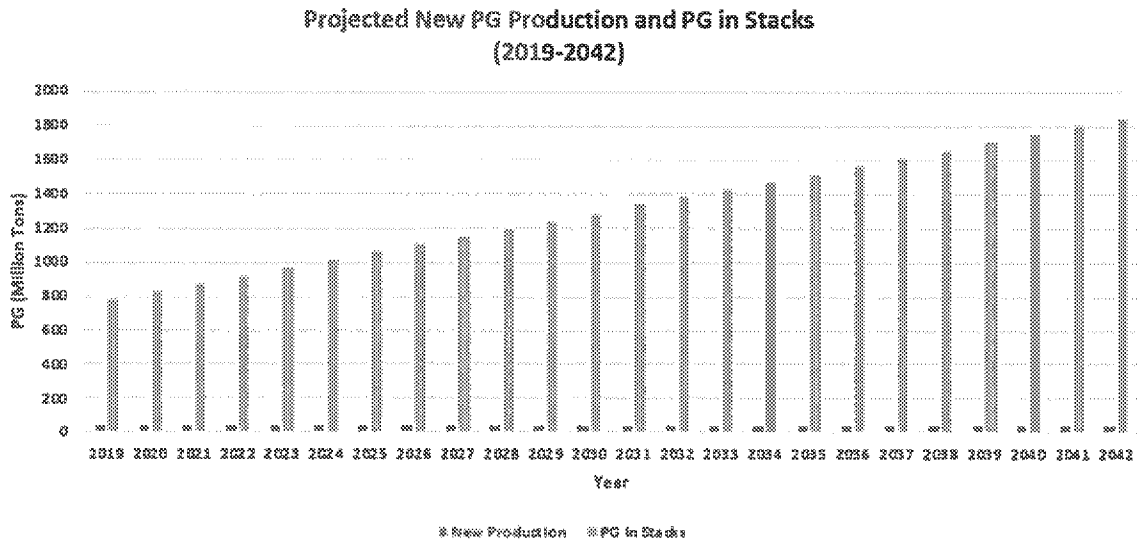

Table 2 summarizes the PG stored in stacks and Figure 1 shows both the PG in stacks and the projected new production of PG. While the period of analysis is 2020-2042, Figure 1 includes data for 2019, as the PG in stack value for 2020 must include the weight for 2019.

Table 2: PG in Stacks

ITEM	ACTIVE STACKS	INACTIVE STACKS	TOTAL
Total PG Stored (million tons)	517	217	734
Weighted Average Per Stack (million tons)	69	65	N/A

Costs to Manage PG

In response to the survey, companies provided annual costs per stack for the following categories[26]:

- Transportation costs — costs to transport PG from the plant to the stacks
- Stack maintenance costs — labor, monitoring, inspection, and reporting costs
- Water management costs — costs for water balancing and water treatment

[25] Figure 1 reflects the current baseline and does not show the PG reuse scenarios discussed later in the analysis.

[26] The cost information was provided by stack and was not tied to PG production levels.

We then use the weights calculated for PG production and PG stored in stacks (see previous subsections) and apply those to the survey data's cost per stack. For the transportation costs, we use the weights for PG production, as transportation costs are incurred in transporting PG from the plant to the stacks; once the PG is in place at the stack, no additional transportation costs are assumed to be incurred. For stack maintenance and water management costs, we use the weights corresponding to PG stored in stacks and apply them to the whole amount of PG stored in a stack. Then, we calculate the weighted average cost per category. To do this, we multiply the corresponding weight by the cost per year per stack, add those products, and divide the resulting sum by the sum of the weights used. Finally, we obtain the average cost per ton by dividing the weighted average by the number of tons per cost category.

The volume of water generated and treated (the water management volume) can be affected by factors such as weather conditions, the manufacturing process, and the age of the PG. The major climate consideration would be variability in precipitation among different geographic regions. While water management volumes would decrease over time due to reduction in size and number of PG stacks, it would not completely disappear. As with all new sustainability strategies, innovation and synergies may lead to additional water management reductions as yet to be determined.

Thus, in practice, the stack water generation and treatment volumes can vary significantly by the location and by the age of the stack. While we asked respondents for typical, current values for water management costs, we are unaware if respondents provided data that represents average climate conditions and PG aging.

Table 3 provides the weight of PG in active stacks, the weighted average costs and the cost per ton for the three cost categories.

Table 3: Weight of PG in Active Stacks and Costs

ITEM	TRANSPORTATION COSTS	STACK MAINTENANCE COSTS	WATER MANAGEMENT COSTS
Weighted Average ($ millions)	7.2	6.8	7.4
Total Tons of PG in Category (million tons)	8.3	570	380
Average Cost Per Ton ($)[27]	0.87	0.012	0.02

[27] Average cost per ton is obtained by dividing the weighted average by total tons of PG. For example, for transportation costs 7.2/8.3=$0.87. Note that values in the table are rounded to two significant figures as noted earlier in the analysis. As a result, total values in table may not sum exactly.

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Other Stack-Related Costs

Survey participants indicated that, in addition to transportation, water management, and stack maintenance costs, there are other long-term costs associated with PG stacks — stack closure costs, water inventory costs, and stack expansion costs. These costs are expected to be incurred in the next five years (between 2020 and 2024).

To avoid providing identifiable information, the surveyed companies provided costs for those long-term categories in dollars per acre of PG stack. In some instances, they provided a lower- and upper-bound estimate for the category. Also, some companies reported zero costs for the category or reported them as part of another category. For this analysis, we create upper- and lower-bound estimates per category, then calculate the middle-point value. Table 4 outlines these costs.

Table 4: Long-Term Costs of PG Management

ITEM	STACK CLOSURE COSTS	WATER INVENTORY COSTS	STACK EXPANSION COSTS	TOTAL	UNIT
Average — Lower Bound	91,000	23,000	220,000	330,000	$/acre
Average — Upper Bound	100,000		240,000	360,000	$/acre
Total Average	96,000	23,000	230,000	350,000	$/acre

Cost Summary

Table 5 summarizes the cost savings due to PG reuse. The most significant savings occur from deferring stack closure and expansion, which together represent almost $350,000 per acre of PG. Since one stack can contain more than 70 million tons of PG, the cost savings of reusing PG are significant.

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Table 5: Short- and Long-Term Costs of PG Management

ITEM	COST	COST TYPE	UNIT
Transportation Costs	0.87	Short-term	$/ton
Stack Maintenance Costs	0.01	Short-term	$/ton
Water Management Costs	0.02	Short-term	$/ton
Stack Closure Costs (includes water inventory costs)	120,000	Long-term	$/acre
Stack Expansion Costs	230,000	Long-term	$/acre

Cost Savings from PG Reuse Scenarios

Baseline Scenario

In this scenario, we quantify the current costs of managing PG at phosphoric acid plants. As outlined in Table 1, the weighted annual PG production is approximately 46 million tons. Figure 1 outlines the total amount of PG expected to be produced per year from 2020 to 2042. It also presents the amount of PG expected to be stored in stacks during that same period. Given the current regulatory restrictions on using PG, this scenario assumes that all new PG produced is put into stacks.

To estimate the costs for the baseline scenario, we first multiply the weighted annual production of PG by the transportation costs per ton ($0.87). We then multiply the weight of PG stacked by the sum of stack maintenance and water management costs per ton of PG ($0.03). Finally, we add the transportation, stack maintenance, and water management costs for the entire period and calculate the net present value (NPV) using discount rates of three and seven percent.

PG Reuse Scenarios

Lower-Bound Scenario

In this scenario, we assume that a percentage of PG produced annually is reused. When PG is reused rather than put into stacks, PG producers incur savings in water management costs, stack maintenance costs, and long-term savings for the amount of PG reused; the only costs they incur are those associated with transport of PG from the facility to the construction site. The NPV of these cost savings minus the transportation costs to the construction site (at discount rates of three and seven percent) are the results for this scenario.

This scenario assumes that five percent of current PG production is reused in each year in 2020 and 2021, 7.5 percent is reused each year in 2022 and 2023, and 10 percent is reused

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in 2024 (see Table 9). Between 2025-2042, the assumed reuse percentage remains at 10 percent. We arrive at this representative reuse scenario by assuming that the PG reuse market will start slowly due to the availability of competing products that already have market share and may be sold through longer-term contracts. Additionally, since PG has been off the market for almost 20 years, this assumption accounts for the idea that it may take PG sellers some time to convince potential customers of PG's beneficial qualities. With these assumptions in place, we calculate water management, and stack maintenance savings by multiplying the sum of the annual weight of PG reused (in tons) plus the weight of PG reused in previous years by $0.03 (see Table 6).[28]

Upper-Bound Scenario

In this scenario, we assume that PG suppliers will offer favorable pricing relative to competing products, effectively promoting greater PG reuse that grows robustly over time. Specifically, we assume that 10 percent of current PG production is reused in 2020, 15 percent is reused in 2021, 20 percent is reused in 2022, 25 percent is reused in 2023, and 30 percent is reused from 2024 (see Table 6). As in the lower-bound scenario, we arrive at this representative reuse scenario by assuming that the PG reuse market will start slowly due to the availability of competing products that already have market share and may be sold through longer-term contracts, and that it may take PG sellers some time to convince potential customers of PG's beneficial qualities. With these assumptions in place, we calculate water management, and stack maintenance savings by multiplying the sum of the annual weight of PG reused (in tons) plus the weight of PG reused in previous years by $0.03 (see Table 6).

[28] Water management and stack maintenance savings are recurrent annual costs. Therefore, they are calculated over the sum of PG reused in a given year plus PG reused in the previous years. For example, for the upper-bound scenario in 2022, water management and stack maintenance savings are calculated over 20.7 tons (sum of amount reused from 2020-2022).

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Table 6: PG Reused

YEAR	LOWER-BOUND SCENARIO PERCENTAGE REUSED (%)	LOWER-BOUND SCENARIO AMOUNT REUSED (MILLION TONS PER YEAR)	UPPER-BOUND SCENARIO PERCENTAGE REUSED (%)	UPPER-BOUND SCENARIO AMOUNT REUSED (MILLION TONS PER YEAR)
2020	5	2.3	10	4.6
2021	5	2.3	15	6.9
2022	7.5	3.5	20	9.2
2023	7.5	3.5	25	12
2024	10	4.6	30	14
2025	10	4.6	30	14
2026	10	4.6	30	14
2027	10	4.6	30	14
2028	10	4.6	30	14
2029	10	4.6	30	14
2030	10	4.6	30	14
2031	10	4.6	30	14
2032	10	4.6	30	14
2033	10	4.6	30	14
2034	10	4.6	30	14
2035	10	4.6	30	14
2036	10	4.6	30	14
2037	10	4.6	30	14
2038	10	4.6	30	14
2039	10	4.6	30	14
2040	10	4.6	30	14
2041	10	4.6	30	14
2042	10	4.6	30	14

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Comparison of Reuse Scenario versus Current Demand for Road Construction

We compare this reuse scenario to the size of local markets as one measure of the reasonableness of the scenario. To validate that our assumptions on PG reuse are feasible given the overall size of the road aggregate market, we contacted the Florida Department of Transportation. We selected Florida as a representative construction market since a majority of the nation's PG is generated in Florida.

Due to the high cost of transporting PG to be used in road construction, we consider that the potential demand for PG is limited to within one day's hauling of the production location, or approximately 200 miles. Both the lower and upper bound scenarios of PG reuse are well within Florida's projected future demand for aggregate for road construction.

Stack Closure Costs

We assume that by reusing a percentage of current production, PG producers will be able to defer stack closure costs. Thus, less PG would need to be stored in stacks, and current stack capacity would last longer. However, it is difficult to predict the number of stacks that may be closed — or expanded — in the period of analysis (and thus estimate the potential cost savings from those deferred stack closures). We believe this to be the case based on insights provided by survey respondents, which suggest that stack closure and stack expansion decisions require long-term strategic planning and are subject to company-specific PG production forecasts and stack capacity.

Recognizing the limitations of generalizing from company-specific conditions to a industry-representative average, in this analysis, we start by assuming that stack closure costs are deferred until 2039 for both the lower- and upper-bound scenarios. The assumption that a stack is closed in 2039 is consistent with historic stack closure reports, as stacks are generally closed after reaching a certain acreage. The purpose of this estimate is to show the potential savings that could arise from deferring stack closure due to PG reuse. For these estimates, the closure cost per acre of PG corresponds to the sum of the water inventory management and stack closure costs ($120,000). Closure occurs in 2039, but the period of analysis covers years until 2042 to allow for the completion of active stack closure activities.

The weight of PG in the survey is provided in tons, while the long-term costs are provided in dollars per acre. Therefore, we next need to estimate how much PG is generally found in one acre. For this estimate, we use a dataset with stack data for Florida.[29] This dataset has information on stack area and length. We assume that all stacks in the Florida dataset are 100 meters in height, have a rectangular base, and have a side slope of 1:3. To estimate the stack width, we divide area by length. Then, we calculate the volume per stack and multiply that volume by an assumed density of PG of 2.3 g/cm^3.[30] (The approach to estimate the stack

[29] State of Florida, "Florida Gypsumstacks."

[30] U.S. EPA, Region 4, Superfund Division, "Engineering Evaluation/Cost Analysis: Closure of the East Gypsum Stack and North Ponds, Mississippi Phosphates Corporation Site, Pascagoula, Jackson County, Mississippi."

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volume was derived from EPA and Florida Department of Environmental Protection sources.[31]) Finally, since the Florida dataset uses data in metric units, we convert square meters into acres. Thus, we conclude that one acre contains approximately 850,000 tons of PG. We then divide the total tons of PG reused in 2039 for the lower- and upper-bound estimates by 850,000 to obtain the equivalent number of acres, multiply it by the actual cost per acre ($120,000), and present the NPV using three and seven percent discount rates.

In this report, based on the estimated reused PG from 2020-2039, we assume that a PG stack of 97 acres is closed in 2039 for the lower-bound scenario and a PG stack of 290 acres is closed in 2039 for the upper-bound scenario.

Stack Expansion Costs

To estimate the potential cost savings from stack expansion, we first divide the weight of PG reused per year by 850,000 to convert it into acres. We then multiply the resulting quotient by $230,000, which is the cost to expand one acre. Finally, we discount the costs using three and seven percent rates.

Stack Maintenance and Water Management Costs

To estimate the potential cost savings from stack maintenance and water management, we first multiply the sum of the annual weight of PG reused (in tons) plus the weight of PG reused in previous years by $0.03. We then calculate the NPV for the entire period of analysis using three and seven percent discount rates.

Transportation Costs to Reuse Location

We assume that PG transportation costs are essentially the same as the cost of transporting alternative materials; therefore, from a social cost perspective, there is no marginal savings by transporting PG or another aggregate. This leads to the conclusion that there are no potential benefits related to savings from transportation costs. Thus, transportation costs are not shown in Table 9 considering that they are zero.

Table 7 provides the key assumptions for PG reuse used in the analysis.

[31] Florida Department of Environmental Protection, "Florida Gypsumstacks, Phosphogypsum Stack System Layer."; U.S. Environmental Protection Agency, "National Emission Standards for Hazardous Air Pollutants; National Emissions Standards for Radon Emissions from Phosphogypsum Stacks; 40 CFR Part 61," 13-19; and Appendix B.

Table 7: Key Assumptions for PG Reuse Scenario

ITEM	LOWER-BOUND SCENARIO	UPPER-BOUND SCENARIO
PG reused in 2020	5% of annual production	10% of annual production
PG reused in 2021	5% of annual production	15% of annual production
PG reused in 2022	7.5% of annual production	20% of annual production
PG reused in 2023	7.5% of annual production	25% of annual production
PG reused in 2024	10% of annual production	30% of annual production
Year in which stack closure occurs	2039	2039
Conversion rate for PG (tons into acres)	850,000	850,000

Results of Cost Savings from PG Reuse

Table 8 shows the total NPV of baseline costs associated with managing PG stacks, which range between $0.88 billion and $1.3 billion at seven and three percent discount rates, respectively.

Table 8: NPV of Baseline Costs to Manage PG

CATEGORY	NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)
Baseline Costs	1,300	880

The total NPV of cost savings between 2020-2042 is presented in Table 9. It shows savings associated with PG reuse ranging between $37 million and $52 million for the lower-bound scenario and $110 million and $160 million for the upper-bound scenario, using seven and three percent discount rates, respectively. It also presents the estimated cost savings for stack closure, water and maintenance management, expansion, and transportation costs. The largest savings result from the deferred stack expansion costs, with the second-largest savings a result of deferred stack closures.

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Table 9: NPV of Cost Savings from PG Reuse

COST CATEGORY[32]	LOWER-BOUND SCENARIO	LOWER-BOUND SCENARIO	UPPER-BOUND SCENARIO	UPPER-BOUND SCENARIO
	NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)
Closure Cost Savings	11	10	33	32
Water and Stack Management Costs	22	13	65	37
Expansion Costs	19	13	57	38
Total Cost Savings	52	37	160	110

Executive Order 13771 Deregulatory Savings

Under E.O. 13771, EPA's action to allow PG to be reused as a road construction material would constitute a deregulatory action and would generate savings that could help EPA achieve its regulatory allocation.

Assuming that EPA either changes its existing regulation to allow a regulatory exemption for PG reuse in road construction or gives a one-time, broad approval of a petition for road construction reuse, EPA's action would constitute a deregulatory action under E.O. 13771. The Office of Management Budget's implementing memorandum for E.O. 13771 draws the distinction between routine regulatory actions and one-time actions that produce on-going savings. Agency actions that require regular agency approvals - e.g., quotas, permits - are not deregulatory actions under E.O. 13771. However, if EPA's approval of PG petitions does not require further approvals, is not conditioned on satisfying reporting requirements, and is broadly applicable to PG producers, it would likely qualify as a deregulatory action. EPA then could count it as part of meeting E.O. 13771's ratio of one deregulatory action for every two regulatory actions.

The action would also generate deregulatory savings. Under E.O. 13771, agencies are granted a regulatory allocation for each fiscal year.[33] The regulatory costs of significant economic regulatory actions and the deregulatory savings must add up to less than the agency's allocation. Agencies must align the savings and costs in the same fiscal year; in this case, the deregulatory savings from allowing PG reuse occur in future years. Table 10 gives the

[32] Transportation costs are omitted from the table as they are zero. Potential revenue obtained from selling PG is not estimated in this report.
[33] "Executive Order 13771 of January 30, 2017, Reducing Regulation and Controlling Regulatory Costs."

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estimated annual savings for the next five years, an illustrative period to demonstrate how savings increase in the near-term before reaching a relatively constant value.

Table 10: Estimated Cost Savings from 2021-2025

TOTAL COST SAVINGS (IN MILLIONS $)	2021	2022	2023	2024	2025
At 3 and 7 Percent Discount Rate	1.1-3.2	1.7-4.5	1.8-5.8	2.4-7.2	2.6-7.7
At 7 Percent Discount Rate	1.1-3.2	1.7-4.5	1.8-5.8	2.4-7.1	2.6-7.6

Summary

In summary, the analysis shows that the potential regulatory cost savings of changes that would allow the reuse of PG ranges between $37 million and $160 million. These results represent the NPV of savings for the period of analysis (2020-2042). These results strongly support the reuse of PG for beneficial applications such as road construction in the U.S. — applications already permitted and used in Europe and elsewhere. Additionally, they support the idea that using PG for road construction offers the possibility of significant savings not only to PG producers, but also to state transportation agencies to the extent they replace a percentage of the aggregates currently used for road construction with PG.

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APPENDIX 1

1. Current producers of phosphoric acid/phosphogypsum (PG) in the U.S., including annual PG production, per stack. If PG production is not available, what is the annual phosphoric acid production (weight)?

Production Company Identifier	2018 Production Amount: PG (T/stack) - Phosphoric Acid (T/year)	2017 Production Amount: PG (T/stack) - Phosphoric Acid (T/year)	2016 Production Amount: PG (T/stack) - Phosphoric Acid (T/year)	Information Provided: PG or Phosphoric Acid?
[Enter response]	[Enter response]	[Enter response]	[Enter response]	[Enter response]

2. Number of PG stacks your company manages and the approximate weight of PG stored in each stack as of 12/31/18. Include those stacks that are inactive, but that have not been closed. Do not include stacks that are permanently closed (not good candidates for PG reuse).

Production Company Identifier	Approximate Weight of PG Stored in Each Stack (T/stack)	Stack Status (Active/ Inactive)
[Enter response]	[Enter response]	[Enter response]

3. With a focus on the process of PG stacking, and an emphasis on active stacking disposal areas, for each active stack, please include the annual costs for: (a)Transporting the gypsum from the phosphoric acid facility to the stack (b)Stack maintenance, including labor costs and monitoring, inspection, reporting requirements (c)Stack process water management, including water balancing and water treatment.

Phosphoric Acid Facility	(a) Annual Gypsum Transportation Cost ($/year)	(b) Stack Maintenance Cost ($/year)	(c) Stack Process Water Management Cost ($/year)	Year in which Costs Are Provided (e.g., $2019 Dollars)
[Enter response]	[Enter response]	[Enter response]	[Enter response]	[Enter response]

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4. Please identify longer term (next five years in aggregate) stack closure costs on a per acre basis (include the costs associated with long term water inventory management)

Phosphoric Acid Company	Stack Closure Management Costs [2020-2024] ($/acre)	Water Inventory Management Costs [2020-2024] ($/acre)	Stack Expansion Costs [2020-2024] ($/acre)	Year in which Costs Are Provided (e.g., $2019 Dollars)
[Enter response]	[Enter response]	[Enter response]	[Enter response]	[Enter response]

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February 2020

Location of Phosphogypsum Stacks

Mosaic:

Plant City: 660 E. County Line Road, Plant City, FL 33565

Bartow: 3200 Hwy 60 W, Bartow, FL 33830

South Pierce: 7450 County Road 630, Mulberry, FL 33860

Riverview: 8813 Hwy 41 S, Riverview, FL 33578

Green Bay: 4390 County Road 640 W, Bartow, FL 33830

New Wales: 3095 Hwy 640 W, Mulberry, FL 33860

Uncle Sam: 7250 Hwy 44, Uncle Sam, LA 70792\

Simplot:

Simplot Phosphates LLC
515 State Hwy 430
Rock Springs WY. 82901

Simplot Don Plant
1150 W Highway 30
Pocatello, Idaho 83204

Nutrien:

White Springs Plant
15843 SE 78th Street
White Springs, Florida 32096

APPENDIX 8

LIST OF DOCUMENTS SUBMITTED FOR THE ADMINISTRATIVE RECORD AS PART OF THE REVISED TFI PETITION

The following is a list of the documents cited in the TFI Petition, the Appendices and Attachments to the Petition. The Administrative Record also includes the Petition, Appendices, and Attachments thereto. If any document cited is not on this list, it is inadvertent and the intent is to include all such documents in the Administrative Record.

Documents Cited in Petition
(Formatted as the document appears in the Petition)

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Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 12/7/2020 2:14:51 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: Request for additional information

Clearly, I failed to bcc you.

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, December 04, 2020 1:49 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: FW: Request for additional information

Hi Jon,

I wanted to follow up on this email from Monday. Did this response get sent out?

Thanks!
Stefanie

From: Bacon, Stefanie
Sent: Monday, November 30, 2020 2:45 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Request for additional information

Thank you Tony.

Jon, I agree with Tony that the response was written well. Could you please coordinate a technical approval from Tom or Dan and then bcc me on the official response? I will make sure that we keep a record of this response along with our other files.

Thank you,
Stefanie

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Monday, November 30, 2020 2:34 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Request for additional information

It's really not a cold call. Jon is listed in the Federal Register as the contact, and as such, can reply directly to the questioner. This is a technical question, so there's no need to involve OPA if the press is not involved.

I think Jon answered the question very well, but given the interest in the topic, Jess and I would recommend that Dan S. or Tom approve all replies before they are sent. Also, we should keep a file of these inquiries and our replies.

Thanks!

Tony

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, November 30, 2020 11:12 AM
To: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: FW: Request for additional information

Tony,

How do we typically handle "cold calls" or in the case below, cold emails ☺ Jon received an email from what seems to be a member of the public. No other affiliation is noted. Is this something that Jon, or Radiation.Questions@epa.gov can reply to, or do we need to loop in OPA?

Thank you,
Stefanie

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Monday, November 30, 2020 10:22 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: FW: Request for additional information

Stef, here is the question and my proposed answer.

Thank you for reaching out with your questions.

The resolution of the groundwater issues raised by SC&A in included in the EPA summary document, "Review of the Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum Prepared for the Fertilizer Institute," in the Section Offsite Individual and Water Pathways, which begins on page 18. For groundwater transport, the SC&A analysis assumed that the phosphogypsum was uncovered by pavement and therefore fully open to infiltration by precipitation, which is not expected to occur, and the resultant risks did not exceed the EPA's threshold for approval. For the crayfish scenario, in order for risk thresholds to be exceeded, surface water must already be contaminated by the radionuclides found in phosphogypsum, which is also not expected to occur.

Rather than require TFI to perform additional analyses, the EPA included conditions which will prevent or minimize contact between phosphogypsum and water. As noted in the EPA summary, "TFI has proposed a generic road design in which phosphogypsum is fully covered by pavement and is therefore protected from infiltration. Additionally, the phosphogypsum is contained in a single, 25 cm layer, which presumably keeps phosphogypsum out of contact with groundwater under typical conditions. As long as these aspects of the generic design are maintained, it is reasonable to expect that the water pathway will not result in unacceptable radiological risks. Should the design change in a way that creates additional exposure of phosphogypsum to water, then this pathway warrants a more involved analysis."

The final approval limits phosphogypsum to a single layer and requires that all phosphogypsum be covered by pavement. With these restrictions in place, the EPA did not require TFI to perform additional analysis of the water pathways. As noted in the EPA's summary, should a different design be proposed, these analyses may be needed at that time.

From: Audrey Ford <audreytford@gmail.com>
Sent: Monday, November 23, 2020 8:21 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: Request for additional information

To: Jonathan P. Walsh, walsh.jonathan@epa.gov

Good Evening Mr. Walsh,
On October 20, 2020, EPA published a notice in the Federal Register regarding EPA's "Approval of the Request for Other Use of Phosphogypsum by the Fertilizer Institute". One of the technical documents supporting this approval, posted on EPA's webpage dedicated to this issue, is titled "Technical Review of The Fertilizer Institute Risk Assessment for Additional Use of Phosphogypsum in Road Base," dated June 10, 2020. Multiple times in this review document, it is suggested that The Fertilizer Institute (TFI) provide further information and/or analysis on specific issues. For example, on page 46, it is recommended that TFI be required to further explore both the groundwater and ingestion of crayfish exposure pathways; on page 45, it is recommended that TFI be requested to revise its reclaimer radon exposure dose calculations, and it is stated that "TFI's evaluation of the Nearest Resident exposure pathways needs to be revised." I am wondering if EPA ever requested these revisions, if TFI ever provided them, and if so, where I might access documentation of those revisions? I have explored all the links included on the EPA's "Approval of Other Uses of Phosphogypsum: Supporting Documents" web page and have been unsuccessful in identifying any such document. Thank you in advance for your time and consideration.

Respectfully,
Audrey Ford

Message

From: Nesky, Anthony [Nesky.Tony@epa.gov]
Sent: 10/14/2020 9:56:07 PM
To: Lee, Raymond [Lee.Raymond@epa.gov]
CC: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: FW: Revised Petition, Response to Questions, etc.
Attachments: 4-7-2020 PG Petition.pdf; Appendix 3 - Metals Risk Screening.pdf; Appendix 4a - Response to Jan 16 2020 Questions.pdf; Appendix 4b - Response to Second Set of EPA Questions.pdf; Appendix 5 - Sampling Report.pdf; Appendix 6 - Economic Report.pdf; Appendix 7 - Location of PG Stacks.pdf; Appendix 8 - Administrative Record.pdf; Attachment A - Road Specs.pdf

Dear Ray:

See Dan's comments below. These materials need to go into the Docket.

Tony

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Wednesday, October 14, 2020 4:19 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: FW: Revised Petition, Response to Questions, etc.

These materials all need to go in the docket.

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Wednesday, April 08, 2020 8:38 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Santillan, Eugenio-Felipe <santillan.eugenio-felipe@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: FW: Revised Petition, Response to Questions, etc.

From: Andy O'Hare <aohare@tfi.org>
Sent: Wednesday, April 08, 2020 8:25 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: Revised Petition, Response to Questions, etc.

Lee and Jon,

Good morning. I hope this finds you both well.

Attached is a updated version of the PG petition, response to the EPA questions on the risk assessment posed in January, response to the questions on the reclaimer scenario, and other assorted supporting appendices, some of which you have already seen. Not attached are Appendices 1 and 2, which accompanied the submittal in October 2018. I would be happy to resend these to your attention, if so desired.

Please confirm that you received these files (9 in all).

I will reach out early next week to discuss next steps in the petition review process and the potential need for a conference call.

Regards,
Andy

Andrew (Andy) T. O'Hare, CAE
Vice President, Public Policy
The Fertilizer Institute
425 Third Street, SW
Suite 950
Washington, DC 20024
(202) 515-2704 (office)
(202) 270-0094 (cell)
aohare@tfi.org

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Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 12/7/2020 2:14:22 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: RE: Request for additional information

Yes, I responded and did not hear back.
Strangely, I attempted to archive the response that I sent, and can't readily locate it. I will add that as a personal to-do item.

Jon

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, December 04, 2020 1:49 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: FW: Request for additional information

Hi Jon,

I wanted to follow up on this email from Monday. Did this response get sent out?

Thanks!
Stefanie

From: Bacon, Stefanie
Sent: Monday, November 30, 2020 2:45 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: Request for additional information

Thank you Tony.

Jon, I agree with Tony that the response was written well. Could you please coordinate a technical approval from Tom or Dan and then bcc me on the official response? I will make sure that we keep a record of this response along with our other files.

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Stefanie

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To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Request for additional information

It's really not a cold call. Jon is listed in the Federal Register as the contact, and as such, can reply directly to the questioner. This is a technical question, so there's no need to involve OPA if the press is not involved.

I think Jon answered the question very well, but given the interest in the topic, Jess and I would recommend that Dan S. or Tom approve all replies before they are sent. Also, we should keep a file of these inquiries and our replies.

Thanks!

Tony

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, November 30, 2020 11:12 AM
To: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: FW: Request for additional information

Tony,

How do we typically handle "cold calls" or in the case below, cold emails ☺ Jon received an email from what seems to be a member of the public. No other affiliation is noted. Is this something that Jon, or Radiation.Questions@epa.gov can reply to, or do we need to loop in OPA?

Thank you,
Stefanie

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Monday, November 30, 2020 10:22 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: FW: Request for additional information

Stef, here is the question and my proposed answer.

Thank you for reaching out with your questions.

Ex. 5 Deliberative Process (DP)

From: Audrey Ford <audreytford@gmail.com>
Sent: Monday, November 23, 2020 8:21 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: Request for additional information

To: Jonathan P. Walsh, walsh.jonathan@epa.gov

Good Evening Mr. Walsh,
On October 20, 2020, EPA published a notice in the Federal Register regarding EPA's "Approval of the Request for Other Use of Phosphogypsum by the Fertilizer Institute". One of the technical documents supporting this approval, posted on EPA's webpage dedicated to this issue, is titled "Technical Review of The Fertilizer Institute Risk Assessment for Additional Use of Phosphogypsum in Road Base," dated June 10, 2020. Multiple times in this review document, it is suggested that The Fertilizer Institute (TFI) provide further information and/or analysis on specific issues. For example, on page 46, it is recommended that TFI be required to further explore both the groundwater and ingestion of crayfish exposure pathways; on page 45, it is recommended that TFI be requested to revise its reclaimer radon exposure dose calculations, and it is stated that "TFI's evaluation of the Nearest Resident exposure pathways needs to be revised." I am wondering if EPA ever requested these revisions, if TFI ever provided them, and if so, where I might access documentation of those revisions? I have explored all the links included on the EPA's "Approval of Other Uses of Phosphogypsum: Supporting Documents" web page and have been unsuccessful in identifying any such document. Thank you in advance for your time and consideration.

Respectfully,
Audrey Ford

Message

From: Nesky, Anthony [Nesky.Tony@epa.gov]
Sent: 10/14/2020 9:52:30 PM
To: Lee, Raymond [Lee.Raymond@epa.gov]
CC: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: FW: Additional TFI Materials for Docket (eom)
Attachments: Appendix 1.pdf; Appendix 2 PG Risk Assessment- Final amended Oct 15-19.pdf

Ray,

Dan wants these in the Docket. I will put it on the website in the interim.

Tony

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Wednesday, October 14, 2020 4:21 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: Additional TFI Materials for Docket (eom)

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 11/10/2020 6:01:55 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
CC: Wieder, Jessica [Wieder.Jessica@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: RE: FOR REVIEW: CMS New Assignment - Candice Marbury - AX-21-000-0547
Attachments: response letter to CMS AX-21-000-0547.pdf

Hi,

Attached is the final signed letter. Patricia will place this into CMS for distribution, so no further action needed.

Thank you for preparing the response.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
http://www.epa.gov/radiation

-----Original Message-----
From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Tuesday, November 10, 2020 10:46 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: FOR REVIEW: CMS New Assignment - Candice Marbury - AX-21-000-0547

That's fine with me.

-----Original Message-----
From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Tuesday, November 10, 2020 10:45 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: FOR REVIEW: CMS New Assignment - Candice Marbury - AX-21-000-0547

Hi Stef,

Thank you. This letter looks good. I have one edit and that is to point out that EPA's review of the risk assessment is available for inspection. Also, What do you all think of referencing this link: https://www.epa.gov/radiation/approval-other-uses-phosphogypsum-supporting-documents

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322 http://www.epa.gov/radiation

-----Original Message-----
From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, November 09, 2020 6:22 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: FOR REVIEW: CMS New Assignment - Candice Marbury - AX-21-000-0547

Good evening Lee,

Attached is a draft response to a control we received last week, as well as the original control letter. Essentially the control asks for EPA to reverse its decision on the use of PG in roads.

This draft response letter has been reviewed by Jon W., Dan, and Jess. The due date for the final response is 11/18.

Please let me know if you have any questions.

Thank you,
Stefanie

-----Original Message-----
From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, November 5, 2020 9:22 AM
To: White, Rick <White.Rick@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Hellberg, Dennis <Hellberg.Dennis@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; Holden, Patricia <Holden.Patricia@epa.gov>
Subject: RE: CMS New Assignment - Candice Marbury - AX-21-000-0547

Jon and Stefanie,
Note that the lead responsibility for responding to the control has been changed to CRIO.
Jon, please support CRIO as they request. Note to all, the request is from a citizen asking us to reverse the decision on the use of PG in roads. There is nothing technical related to it.
Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

-----Original Message-----
From: White, Rick <White.Rick@epa.gov>
Sent: Thursday, November 05, 2020 9:01 AM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Hellberg, Dennis <Hellberg.Dennis@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; Holden, Patricia <Holden.Patricia@epa.gov>
Subject: FW: CMS New Assignment - Candice Marbury - AX-21-000-0547

Good Morning Tony-

I believe this makes more sense for CRIO to coordinate the response. If you have any questions or concerns, please let me know.

Thanks.

Rick

-----Original Message-----
From: Holden, Patricia <Holden.Patricia@epa.gov>
Sent: Thursday, November 05, 2020 8:39 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Subject: FW: CMS New Assignment - Candice Marbury - AX-21-000-0547

Good Morning,

The attached CMS was assigned to your center. I've attached the incoming letter and copied the below information with the due date of November 18, 2020.

Patricia Holden
Secretary
Radiation Protection Division
202-343-9458

Citizen Information
Generate Control Slip

Citizen/Originator: 1). Lynen, Richard F. - 2209 Summit View Drive, Valrico, FL 33596
Constituent:
Committee: Sub-Committee:
Control Information View Correspondence

Control Number: AX-21-000-0547 Alternate Number:
Status: Pending Closed Date: N/A
Due Date: Nov 18 2020 # of Extensions: 0 Letter Date: Oct 20 2020 Received Date: Nov 02 2020
Addressee: AD-Administrator Addressee Org: EPA Contact Type: LTR (Letter) Priority Code: Normal File Code: 401_1006_a Administrative Management - Controlled and major correspondence for employees other than senior officials
Signature: DX-Direct Reply
CC:
R4 - Region 4 -- Immediate Office

Search CC

Signature Date: N/A
Primary Subject: Reverse decision for use of radioactive phospho-gypsum for use in road building
Secondary Subject:
Instructions: DX-Respond directly to this citizen's questions, statements, or concerns Instruction Notes:
General Notes:

Lead Information

Lead Author: N/A

Lead Assignments:

Assigner	Assignee	Office	Assigned	Due Date	Completed	Instructions
Jacqueline Leavy	OAR-ORIA	OAR-ORIA	11/03/2020	11/18/2020	N/A	DX-Respond directly to this citizen's questions, statements, or concerns

Supporting Information

Supporting Author: N/A

Supporting Assignments:

Assigner	Assignee	Office	Assigned Date
No records found.			

History

Action By	Office	Date	Action
Jacqueline Leavy	OEX	11/02/2020	Assign OAR as lead office
Maria Carroll	OAR	11/02/2020	Accepted the group assignment
Jenny Noonan	OAR-OAQPS	11/03/2020	Blanche Scott proxy for Jenny Noonan: Accepted the group assignment
Jenny Noonan	OAR-OAQPS	11/03/2020	Blanche Scott proxy for Jenny Noonan: Sent to Jacqueline Leavy for Reassignment Request
Jacqueline Leavy	OEX	11/03/2020	Request for Reassignment Approved
Jacqueline Leavy	OEX	11/03/2020	Assign OAR-ORIA as lead office
Candice Marbury	OAR-ORIA	11/04/2020	Accepted the group assignment

Comments

Commentator	Date	Comments
Jenny Noonan	11/03/2020	This should go to ORIA - specifically, the Radiation Protection Division.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
Washington, DC 20460

November 10, 2020

OFFICE OF
AIR AND
RADIATION

Richard F. Lynen
2209 Summit View Drive
Valrico, FL 33596

Dear Mr. Lynen:

Thank you for writing to the U.S. Environmental Protection Agency (EPA). Administrator Wheeler asked that I respond to your October 20, 2020 letter requesting that the EPA reverse its approval of the use of phosphogypsum in government road construction projects. We appreciate your concerns in this matter.

The EPA's decision to allow phosphogypsum in government road construction projects was based on risk analyses which showed that the use of phosphogypsum in these projects would present no greater risk to members of the public than would be expected if the phosphogypsum were left in the stack. By approving the use of phosphogypsum in government road construction projects, the EPA granted state and local governments the opportunity to investigate whether the use of phosphogypsum in road projects would be appropriate in their jurisdictions. The final decision to incorporate phosphogypsum as a material in road projects rests entirely at the state and local level, and not with the companies that generate phosphogypsum. One condition of the EPA approval is that state or local agencies proposing road projects that use phosphogypsum inform the public of the proposed use and provide an opportunity for public review of the project and associated documents, including the risk assessment upon which the EPA's decision was based.

Once again, thank you for taking the time to follow these important issues and to share your feedback. I appreciate the opportunity to be of service and trust the information provided is helpful. More information on this topic, including EPA's report containing the technical review of the risk assessment, is available at https://www.epa.gov/radiation/approval-other-uses-phosphogypsum-supporting-documents.

Sincerely,

LEE ANN VEAL Digitally signed by LEE ANN VEAL
Date: 2020.11.10 13:00:01 -05'00'

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 11/10/2020 3:46:26 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]
CC: Wieder, Jessica [Wieder.Jessica@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: RE: FOR REVIEW: CMS New Assignment - Candice Marbury - AX-21-000-0547

That's fine with me.

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From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Tuesday, November 10, 2020 10:45 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
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Redacted

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322 http://www.epa.gov/radiation

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Subject: RE: CMS New Assignment - Candice Marbury - AX-21-000-0547

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Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

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Subject: FW: CMS New Assignment - Candice Marbury - AX-21-000-0547

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Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Subject: FW: CMS New Assignment - Candice Marbury - AX-21-000-0547

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Patricia Holden
Secretary
Radiation Protection Division
202-343-9458

Citizen Information
Generate Control Slip

Citizen/Originator: 1). Lynen, Richard F. - 2209 Summit View Drive, Valrico, FL 33596
Constituent:
Committee: Sub-Committee:
Control Information View Correspondence

Control Number: AX-21-000-0547 Alternate Number:
Status: Pending Closed Date: N/A
Due Date: Nov 18 2020 # of Extensions: 0 Letter Date: Oct 20 2020 Received Date: Nov 02 2020
Addressee: AD-Administrator Addressee Org: EPA Contact Type: LTR (Letter) Priority Code: Normal File Code: 401_1006_a Administrative Management - Controlled and major correspondence for employees other than senior officials
Signature: DX-Direct Reply
CC:
R4 - Region 4 -- Immediate Office

Search CC

Signature Date: N/A
Primary Subject: Reverse decision for use of radioactive phospho-gypsum for use in road building
Secondary Subject:
Instructions: DX-Respond directly to this citizen's questions, statements, or concerns Instruction Notes:
General Notes:

Lead Information

Lead Author: N/A

Lead Assignments:

Assigner	Assignee	Office	Assigned	Due Date	Completed	Instructions
Jacqueline Leavy	OAR-ORIA	OAR-ORIA	11/03/2020	11/18/2020	N/A	DX-Respond directly to this citizen's questions, statements, or concerns

Supporting Information

Supporting Author: N/A

Supporting Assignments:

Assigner	Assignee	Office	Assigned	Date
No records found.				

History

Action By	Office	Date	Action
Jacqueline Leavy	OEX	11/02/2020	Assign OAR as lead office
Maria Carroll	OAR	11/02/2020	Accepted the group assignment
Jenny Noonan	OAR-OAQPS	11/03/2020	Blanche Scott proxy for Jenny Noonan: Accepted the group assignment
Jenny Noonan	OAR-OAQPS	11/03/2020	Blanche Scott proxy for Jenny Noonan: Sent to Jacqueline Leavy for Reassignment Request
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Candice Marbury	OAR-ORIA	11/04/2020	Accepted the group assignment

Comments

Commentator	Date	Comments
Jenny Noonan	11/03/2020	This should go to ORIA - specifically, the Radiation Protection Division.

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 4/1/2020 3:02:05 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
CC: Stuenkel, David [Stuenkel.David@epa.gov]; David Stuenkel [davidstuenkel@live.com]
Subject: TFI risk assessment review - recurring technical meeting
Attachments: TFI_Weekly_updates_agenda_4-1-2020.docx

If you're not able to Skype in.

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 9/26/2019 7:15:23 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
CC: Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: Very Draft TFI Comms Plan

Ex. 5 Deliberative Process (DP)

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, September 23, 2019 11:02 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: Very Draft TFI Comms Plan

Jon,

Here's the basic communications plan that I've drafted for TFI. It was based on TFI briefing materials, but consider it still in very draft form. We can discuss today, and continue to modify as the TFI application moves forward.

Thanks,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Appointment

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 2/3/2020 10:16:32 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Bacon, Stefanie [Bacon.stefanie@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
CC: Stuenkel, David [Stuenkel.David@epa.gov]

Subject: TFI risk assessment review - recurring technical meeting
Attachments: TFI_Weekly_updates_agenda_2-4-2020.docx
Location: DCRoomWest1424/ORIA

Start: 2/4/2020 4:00:00 PM
End: 2/4/2020 5:00:00 PM
Show Time As: Tentative

Recurrence: Weekly
every Tuesday from 11:00 AM to 12:00 PM

Agenda attached

Join Skype Meeting

Trouble Joining? Try Skype Web App

Join by phone

Ex. 6 Personal Privacy (PP) English (United States)

Find a local number

Ex. 6 Personal Privacy (PP)

Forgot your dial-in PIN? | Help

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 1/14/2020 3:36:24 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
CC: Stuenkel, David [Stuenkel.David@epa.gov]
Subject: RE: TFI risk assessment review - recurring technical meeting
Attachments: TFI_Weekly_updates_agenda_1-14-2019.docx

Today's agenda. See you soon.

-----Original Appointment-----
From: Walsh, Jonathan
Sent: Monday, November 25, 2019 4:24 PM
To: Bacon, Stefanie; Walsh, Jonathan; Lee Veal (Veal.Lee@epa.gov); Tom Peake; Schultheisz, Daniel; Diaz, Charlene; Wieder, Jessica; Egidi, Philip; Rustick, Joseph; Nagata, Jonathan; White, Rick; Santillan, Eugenio-Felipe; Lee, Raymond
Cc: Stuenkel, David
Subject: TFI risk assessment review - recurring technical meeting
When: Tuesday, January 21, 2020 11:00 AM-12:00 PM (UTC-05:00) Eastern Time (US & Canada).
Where: DCRoomWest1424/ORIA

Join Skype Meeting

Trouble Joining? Try Skype Web App

Join by phone

Ex. 6 Personal Privacy (PP) English (United States)

Find a local number

Ex. 6 Personal Privacy (PP)

Forgot your dial-in PIN? | Help

please contact FERC Online Support at *FERCOnlineSupport@ferc.gov,* (866) 208–3676 (toll free), or (202) 502–8659 (TTY).

In lieu of electronic filing, you may submit a paper copy. Submissions sent via U.S. Postal Service must be addressed to, Kimberly D. Bose, Secretary, Federal Energy Regulatory Commission, 888 First Street NE, Room 1A, Washington, DC 20426. Submissions sent via any other carrier must be addressed to, Kimberly D. Bose, Secretary, Federal Energy Regulatory Commission, 12225 Wilkins Avenue, Rockville, Maryland 20852. The first page of any filing should include docket number P–13417–008. Comments emailed to Commission staff are not considered part of the Commission record.

In addition to publishing the full text of this document in the **Federal Register**, the Commission provides all interested persons an opportunity to view and/or print the contents of this document via the internet through the Commission's Home Page (*http://ferc.gov*) using the "eLibrary" link. Enter the docket number excluding the last three digits in the docket number field to access the document. At this time, the Commission has suspended access to the Commission's Public Reference Room, due to the proclamation declaring a National Emergency concerning the Novel Coronavirus Disease (COVID–19), issued by the President on March 13, 2020. For assistance, contact the Federal Energy Regulatory Commission at *FERCOnlineSupport@ferc.gov* or call toll-free, (886) 208–3676 or TYY, (202) 502–8659.

Dated: October 14, 2020.

Kimberly D. Bose,

Secretary.

[FR Doc. 2020–23158 Filed 10–19–20; 8:45 am]

BILLING CODE 6717–01–P

DEPARTMENT OF ENERGY

Federal Energy Regulatory Commission

Combined Notice of Filings

Take notice that the Commission has received the following Natural Gas Pipeline Rate and Refund Report filings:

Docket Number: PR20–70–001.

Applicants: Regency Intrastate Gas LP.

Description: Tariff filing per 284.123(b),(e)/: Revised Operating Statement to be effective 6/2/2020.

Filed Date: 10/13/2020.

Accession Number: 202010135157.

Comments/Protests Due: 5 p.m. ET 11/3/2020.

Docket Numbers: RP20–1229–001.

Applicants: Cheniere Corpus Christi Pipeline, LP.

Description: Tariff Amendment: Housekeeping Supplemental Filing to be effective 10/28/2020.

Filed Date: 10/13/20.

Accession Number: 20201013–5193.

Comments Due: 5 p.m. ET 10/26/20.

Docket Numbers: RP21–53–000.

Applicants: Panhandle Eastern Pipe Line Company, LP.

Description: § 4(d) Rate Filing: Housekeeping Filing on 10–13–20 to be effective 11/13/2020.

Filed Date: 10/13/20.

Accession Number: 20201013–5151.

Comments Due: 5 p.m. ET 10/26/20.

Docket Numbers: RP21–54–000.

Applicants: El Paso Natural Gas Company, L.L.C.

Description: § 4(d) Rate Filing: Non-Conforming Agreements Update (NMG) to be effective 1/1/2021.

Filed Date: 10/13/20.

Accession Number: 20201013–5165.

Comments Due: 5 p.m. ET 10/26/20.

The filings are accessible in the Commission's eLibrary system (*https://elibrary.ferc.gov/idmws/search/fercgensearch.asp*) by querying the docket number.

Any person desiring to intervene or protest in any of the above proceedings must file in accordance with Rules 211 and 214 of the Commission's Regulations (18 CFR 385.211 and 385.214) on or before 5:00 p.m. Eastern time on the specified comment date. Protests may be considered, but intervention is necessary to become a party to the proceeding.

eFiling is encouraged. More detailed information relating to filing requirements, interventions, protests, service, and qualifying facilities filings can be found at: *http://www.ferc.gov/docs-filing/efiling/filing-req.pdf.* For other information, call (866) 208–3676 (toll free). For TTY, call (202) 502–8659.

Dated: October 14, 2020.

Nathaniel J. Davis, Sr.,

Deputy Secretary.

[FR Doc. 2020–23205 Filed 10–19–20; 8:45 am]

BILLING CODE 6717–01–P

ENVIRONMENTAL PROTECTION AGENCY

[FRL–10015–95–Region 1]

2020 Annual Meeting of the Ozone Transport Commission

AGENCY: Environmental Protection Agency (EPA).

ACTION: Notice; meeting.

SUMMARY: The United States Environmental Protection Agency (EPA) is announcing the 2020 Annual Meeting of the Ozone Transport Commission (OTC). The meeting agenda will include topics regarding reducing ground-level ozone precursors.

DATES: The meeting will be held on November 18, 2020 starting at 9 a.m. and ending at noon.

ADDRESSES: Virtual meeting. Further information on the details for the virtual public meeting will be available at *http://www.otcair.org.*

FOR FURTHER INFORMATION CONTACT:

For documents and press inquiries contact: Ozone Transport Commission, 89 South St., Suite 602, Boston, MA 02111; (617) 259–2005; email: *ozone@otcair.org*; website: *http://www.otcair.org.*

For registration: To register for the virtual meeting, please use the online registration form available at *http://www.otcair.org,* or contact the OTC at (617) 259–2005 or by email at *ozone@otcair.org.*

SUPPLEMENTARY INFORMATION: The Clean Air Act Amendments of 1990 contain Section 184 provisions for the Control of Interstate Ozone Air Pollution. Section 184(a) establishes an Ozone Transport Region (OTR) comprised of the States of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, parts of Virginia and the District of Columbia. The purpose of the OTC is to address ground-level ozone formation, transport, and control within the OTR.

Type of Meeting: Open.

Agenda: Copies of the final agenda will be available from the OTC office (617) 259–2005; by email: *ozone@otcair.org* or via the OTC website at *http://www.otcair.org.*

Dated: October 14, 2020.

Dennis Deziel,

Regional Administrator, EPA Region 1.

[FR Doc. 2020–23122 Filed 10–19–20; 8:45 am]

BILLING CODE 6560–50–P

ENVIRONMENTAL PROTECTION AGENCY

[EPA–HQ–OAR–2020–0442; FRL–10014–36–OAR]

Approval of the Request for Other Use of Phosphogypsum by the Fertilizer Institute

AGENCY: Environmental Protection Agency (EPA).

ACTION: Notice.

SUMMARY: The Environmental Protection Agency (EPA) is approving, subject to certain conditions, a request by The Fertilizer Institute for use of phosphogypsum in government road projects. This decision and supporting information is being made available to the public through this notice. Under the Clean Air Act, the EPA may approve a request for other use of phosphogypsum if it determines that the proposed use is at least as protective of human health as placement in a stack, which is the designated management method. With this approval, and in accordance with its terms and conditions, government entities may use phosphogypsum for road construction projects.

DATES: October 20, 2020.

FOR FURTHER INFORMATION CONTACT: Jonathan P. Walsh, Radiation Protection Division, Office of Radiation and Indoor Air, Mail Code 6608T, Environmental Protection Agency, 1200 Pennsylvania Ave. NW, Washington, DC 20460; telephone number: (202) 343–9238; fax number: (202) 343–2304; email address: *walsh.jonathan@epa.gov.*

Organization of this document. The information in this notice is organized as follows:

I. General Information
A. How can I get copies of this document and other related information?
II. Background and Overview of Decision
A. The EPA's 1992 Risk Assessment
B. Request by The Fertilizer Institute
C. TFI's Risk Assessment
D. Terms and Conditions of the Approval

SUPPLEMENTARY INFORMATION:

I. General Information

A. How can I get copies of this document and other related information?

1. *Docket.* The EPA has established a docket for this action under Docket ID No. EPA–HQ–OAR–2020–0442. Publicly available docket materials are available either electronically through *www.regulations.gov* or in hard copy at the Air and Radiation Docket in the EPA Docket Center, (EPA/DC) EPA West, Room 3334, 1301 Constitution Ave. NW, Washington, DC. The EPA Docket Center Public Reading Room is open from 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding legal holidays. The telephone number for the Public Reading Room is (202) 566–1744, and the telephone number for the Air and Radiation Docket is (202) 566–1742.

2. *Electronic Access.* You may access this **Federal Register** document electronically from the Government Printing Office under the "**Federal Register**" listings at FDSys (*http://www.gpo.gov/fdsys/browse/collection.action?collectionCode=FR*).

II. Background and Overview of Decision

Phosphogypsum stacks are large piles of waste from wet acid phosphorous production. There are more than 60 stacks of phosphogypsum located in 13 different states. The majority of these stacks are located in the southeastern region of the United States. Because the phosphate ore used to produce the phosphoric acid contains relatively high concentrations of uranium and radium, phosphogypsum stacks also contain high concentrations of these elements. The presence of radium in the stacks causes them to release radon gas into the atmosphere.

The EPA regulates the management of phosphogypsum based on its elevated levels of radium and its decay products, including radon gas, which is classified as a hazardous air pollutant under the Clean Air Act. As required by 40 CFR part 61, subpart R (hereafter "Subpart R"), phosphogypsum must be disposed of in engineered piles, called stacks, with the exception of limited use for agricultural and research purposes. In addition, applicants may request approval of other uses of phosphogypsum by following the process prescribed in 40 CFR 61.206.

A. The EPA's 1992 Risk Assessment

The EPA initially established the requirement that phosphogypsum be placed into stacks without any exceptions (54 FR 51674, December 15, 1989). In response to petitions for reconsideration, the EPA re-evaluated the risks of selected applications of phosphogypsum against the risks from stacking (57 FR 23305, June 3, 1992).[1] The EPA determined that the use of phosphogypsum in limited agricultural and indoor research activities could be as protective of human health, in the short- and long-term, as stacking. These approved uses were incorporated into Subpart R at 40 CFR 61.204–205.

The EPA also assessed the use of phosphogypsum in road construction. While the risks were found to be acceptable from most of the exposure scenarios analyzed, the potential risks to residents of dwellings constructed on an abandoned road were calculated to be unacceptably high. The EPA therefore did not approve road construction as a categorical use of phosphogypsum. The EPA did, however, define in 40 CFR 61.206 a process to request approval of other uses of phosphogypsum, including a risk assessment demonstrating that the proposed use is at least as protective of human health, in the short- and long-term, as placement in a stack. As stated in the preamble to the final rule, the measure of protectiveness is lifetime risk of fatal cancer to individuals. In connection with the removal of phosphogypsum from stacks for authorized uses, the EPA incorporated sampling, certification, and record-keeping requirements into Subpart R at 40 CFR 61.207 through 61.209.

B. Request by The Fertilizer Institute

On October 15, 2019, The Fertilizer Institute (TFI) submitted its initial "Request for Approval of Additional Uses of Phosphogypsum Pursuant to 40 CFR 61.206," requesting that EPA approve the use of phosphogypsum in road construction. Subsequently, on April 7, 2020, TFI submitted, on behalf of its members that own or operate phosphogypsum stacks, a revised request: "Revised Request for Approval of Additional Uses of Phosphogypsum Pursuant to 40 CFR 61.206: Use in Road Construction Projects Authorized by Federal, State and Local Departments of Transportation or Public Works."

TFI requested that phosphogypsum be approved specifically for government road projects authorized by federal, state and local Departments of Transportation (DOT) or Public Works (PW), and conducted as part of a government road project using appropriate, generally accepted road construction standards and specifications such as ASTM,[2] Federal Highway Administration, federal or state DOT standards and specifications, or standards developed or approved in consultation with the appropriate regulatory DOT or PW authorities. Notably, as envisioned by the request, the submitter of the request (TFI) would not be the entity using the phosphogypsum, although its members may supply the phosphogypsum to the end user (*i.e.,* the government agency responsible for the road construction project). To address this situation, the terms and conditions of the approval require that the phosphogypsum supplier (stack owner or operator) and the end user each provide information to the EPA, as appropriate, prior to removal of phosphogypsum from the stack.

TFI estimates that the cost of transportation would make the use of

[1] "Potential Uses of Phosphogypsum and Associated Risks: Background Information Document," EPA 402–R92–002, May 1992.

[2] Formerly the American Society for Testing and Materials, now ASTM International.

phosphogypsum uneconomical at distances greater than about 200 miles from a stack.[3] In that case, the regional distribution of phosphogypsum stacks suggests that its use for road construction would likely be concentrated in the southeastern part of the country but could also occur in western states such as Idaho and Wyoming.

C. TFI's Risk Assessment

As required by Subpart R, TFI submitted a risk assessment as part of its request.[4] The risk assessment assessed potential exposures to individuals in various scenarios involving road users, nearby residents, and road construction workers. TFI's exposure scenarios and modeling approaches were largely consistent with the EPA's 1992 analysis, as were the overall results.

The EPA finds TFI's risk assessment to adequately demonstrate that the use of phosphogypsum in road construction will be at least as protective of human health, in the short- and long-term, as stacking.[5] However, as in 1992, the EPA remains concerned about potential exposures should the road become abandoned, particularly for a residence built on road material containing phosphogypsum. The EPA does not agree that TFI's assumptions in its analysis of this scenario, such as the use of radon resistant home construction techniques, could be relied upon to limit the potential risks to a future residential individual from such an occurrence. In this case, however, the EPA believes that this risk can be acceptably mitigated by including appropriate terms and conditions in the approval.

In defining its request and exposure scenarios, TFI's risk assessment assumes certain limitations involving the construction and placement of roads. For example, phosphogypsum incorporated into the road base and the road surface is limited in its radium-226 concentration and is assumed to be mixed with other materials in limited proportions. The terms and conditions of the approval reflect these assumptions and limitations.

D. Terms and Conditions of the Approval

The EPA has determined that, subject to the terms and conditions summarized below, phosphogypsum may be removed from stacks and used in government road projects, as requested by TFI. This approval to use phosphogypsum in road construction does not authorize the removal of any phosphogypsum from any stacks or the use of any phosphogypsum for road construction unless and until the information required by the "Initial Conditions," below, is provided to EPA. Only after such information is provided to EPA, may phosphogypsum be removed from stacks and used in road construction, further provided that the conditions expressed in "Other Conditions," below, continue to be met. A complete listing of the terms and conditions applicable to this approval may be found in the approval letter.[6] Additional supporting documentation, such as the complete TFI request and risk assessment, are also in the docket.

1. Initial Conditions

Prior to the distribution and/or use of phosphogypsum for any government road project, the owner or operator of the stack from which phosphogypsum is to be distributed or the governmental entity responsible for building and maintaining the road, as appropriate, must submit to the Agency all information required by 40 CFR 61.206(b), as more specifically described in the approval letter.

2. Other Conditions [7]

Subsequent to the provision of the initial required information to EPA, phosphogypsum may be used in government road projects in accordance with additional conditions, as stated in the approval letter, including, for example, conditions related to:

- Continued control, maintenance, and use of the road;
- Sampling, certification, and record-keeping requirements in 40 CFR 61.206(d) and 61.207 through 61.209;
- Construction of the road consistent with the assumptions, scenarios, limitations, and parameters analyzed in TFI's risk assessment, including an average radium content of no more than 35 pCi/g, no more than 2.25% PG by weight in surface pavement and no more than 50% PG by weight in the road base; and
- Notification and availability of information for the public and road construction workers on the use of phosphogypsum in the road project.

Any use of phosphogypsum not consistent with the terms and conditions and any other limitations set forth in this approval shall be construed as unauthorized distribution of phosphogypsum and may constitute a violation of or noncompliance with 40 CFR part 61, subpart R. This approval is pursuant to Subpart R promulgated under the authority of the Clean Air Act. This approval does not relieve TFI, phosphogypsum stack owners or operators or resellers, retailers, distributors, or end users or other entities handling, processing or using phosphogypsum of responsibility to comply with other applicable laws and regulations.

Andrew Wheeler,

Administrator.

[FR Doc. 2020–23154 Filed 10–19–20; 8:45 am]

BILLING CODE 6560–50–P

[3] "Economic Analysis of Phosphogypsum Reuse," prepared for TFI by Policy Navigation Group, submitted as Appendix 6 to TFI's Revised Request, December 2019, page 19.

[4] "Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum," prepared for TFI by Arcadis Canada Inc., submitted as Appendix 2 to TFI's Revised Request, October 2019.

[5] "Review of the Radiological Risk Assessment Submitted in Support of Request for Approval of Other Use of Phosphogypsum," October 2019, The Fertilizer Institute.

[6] Letter from Andrew Wheeler, Administrator, Environmental Protection Agency, to Corey Rosenbusch, President and CEO, The Fertilizer Institute, Docket No. EPA–HQ–OAR–2020–0442.

[7] In addition to the information required by 40 CFR 61.206(b), as noted in connection with the "Initial Conditions," the "Other Conditions" include conditions associated with the requirements of 40 CFR 61.206(d) and 61.207–61.209; conditions inherent in the nature of or limitations or assumptions associated with TFI's request; and conditions imposed under the EPA's authority and discretion under 40 CFR 61.206(e). The EPA believes that these conditions are either required by 40 CFR part 61, subpart R or are reasonably appropriate to help provide continued assurance that the use is at least as protective as disposal of phosphogypsum in stacks and will ensure that the removal of phosphogypsum from stacks and use in government road projects will be consistent with TFI's request and will occur with public notice and appropriate information availability.

ENVIRONMENTAL PROTECTION AGENCY

[EPA–HQ–OPPT–2020–0077; FRL–10015–81]

Certain New Chemicals; Receipt and Status Information for September 2020

AGENCY: Environmental Protection Agency (EPA).

ACTION: Notice.

SUMMARY: EPA is required under the Toxic Substances Control Act (TSCA), as amended by the Frank R. Lautenberg Chemical Safety for the 21st Century Act, to make information publicly available and to publish information in the **Federal Register** pertaining to submissions under TSCA Section 5, including notice of receipt of a Premanufacture notice (PMN), Significant New Use Notice (SNUN) or Microbial Commercial Activity Notice (MCAN), including an amended notice or test information; an exemption

Message

From: Ruth McBurney [rmcburney@crcpd.org]
Sent: 10/20/2020 1:28:47 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]; Mendy Cremeans [mcremeans@crcpd.org]
Subject: RE: EPA Approval of Request for Other Use of Phosphogypsum

Thanks, Stephanie. We will send this on to the Board and perhaps the state directors.

Bests,
Ruth

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, October 20, 2020 8:58 AM
To: Ruth McBurney <rmcburney@crcpd.org>; Mendy Cremeans <mcremeans@crcpd.org>
Subject: EPA Approval of Request for Other Use of Phosphogypsum

Good morning Ruth and Mendy,

During our last board call, I mentioned an upcoming EPA action related to phosphogypsum. Now that it is official, I wanted to let you know that on October 14, EPA approved a request by The Fertilizer Institute (TFI) for use of phosphogypsum in government road construction projects. This approval is granted under the Clean Air Act and the provisions in 40 CFR 61.206, which allow EPA to approve other uses of phosphogypsum if they can be demonstrated to be at least as protective as keeping the material in a stack, which is the designated management method.

This approval is subject to terms and conditions, and we are not aware of any such projects under consideration at this time. A government agency proposing to use phosphogypsum in this manner would have to submit additional information to EPA and provide an opportunity for the public to review the proposal and documents related to this approval, including the risk assessment submitted by TFI. A key condition is that the road not be abandoned or converted for non-road uses, unless additional risk analyses are conducted and EPA is notified.

Attached are the approval letter and the Federal Register notice, which was published today. You can find more information at https://www.epa.gov/radiation/subpart-r-national-emission-standards-radon-emissions-phosphogypsum-stacks. The official docket for this action can be accessed through www.regulations.gov, search for Docket No. EPA-HQ-OAR-2020-0442.

Please let me know if you have any questions. Thanks.
Stefanie

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 12/7/2020 3:01:41 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: FW: Request for additional information
Attachments: EPA-HQ-OAR-2020-0442-0018.pdf

Found it.

From: Walsh, Jonathan
Sent: Tuesday, December 01, 2020 2:06 PM
To: Audrey Ford <audreytford@gmail.com>
Subject: RE: Request for additional information

Dear Ms. Ford,

Thank you for reaching out with your questions.

The EPA's resolution of the groundwater issues raised by SC&A is included in the EPA summary document, "Review of the Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum Prepared for the Fertilizer Institute," in the section Offsite Individual and Water Pathways, which begins on page 18. I've attached a copy of the document to this email. For its groundwater transport calculations, the SC&A analysis assumed that the phosphogypsum was uncovered by pavement and therefore fully open to infiltration by precipitation, which is not expected to occur. The resultant risks still did not exceed the EPA's threshold for approval. For the crayfish ingestion scenario, in order for risk thresholds to be exceeded, surface water was assumed to already be contaminated by the radionuclides found in phosphogypsum, which is also not expected to occur.

Rather than require TFI to perform additional analyses, the EPA included conditions in its approval which will prevent or minimize contact between phosphogypsum and water. As noted in the EPA summary, "TFI has proposed a generic road design in which phosphogypsum is fully covered by pavement and is therefore protected from infiltration. Additionally, the phosphogypsum is contained in a single, 25 cm layer, which presumably keeps phosphogypsum out of contact with groundwater under typical conditions. As long as these aspects of the generic design are maintained, it is reasonable to expect that the water pathway will not result in unacceptable radiological risks. Should the design change in a way that creates additional exposure of phosphogypsum to water, then this pathway warrants a more involved analysis."

The final approval limits phosphogypsum to a single 25 cm layer, and requires that all phosphogypsum be covered by pavement. With these restrictions in place, the EPA did not require TFI to perform additional analysis of the water pathways. As noted in the EPA's summary, if the design changes or a different design is proposed, these analyses may be required by the EPA at that time.

Hopefully this is helpful. Please reach out if you have any additional questions.

Jonathan P. Walsh, CHP
Physical Scientist
U.S. EPA, Radiation Protection Division
Center for Waste Management and Regulations
202-343-9238
202-841-9880 (mobile)

From: Audrey Ford <audreytford@gmail.com>
Sent: Monday, November 23, 2020 8:21 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: Request for additional information

To: Jonathan P. Walsh, walsh.jonathan@epa.gov

Good Evening Mr. Walsh,
On October 20, 2020, EPA published a notice in the Federal Register regarding EPA's "Approval of the Request for Other Use of Phosphogypsum by the Fertilizer Institute". One of the technical documents supporting this approval, posted on EPA's webpage dedicated to this issue, is titled "Technical Review of The Fertilizer Institute Risk Assessment for Additional Use of Phosphogypsum in Road Base," dated June 10, 2020. Multiple times in this review document, it is suggested that The Fertilizer Institute (TFI) provide further information and/or analysis on specific issues. For example, on page 46, it is recommended that TFI be required to further explore both the groundwater and ingestion of crayfish exposure pathways; on page 45, it is recommended that TFI be requested to revise its reclaimer radon exposure dose calculations, and it is stated that "TFI's evaluation of the Nearest Resident exposure pathways needs to be revised." I am wondering if EPA ever requested these revisions, if TFI ever provided them, and if so, where I might access documentation of those revisions? I have explored all the links included on the EPA's "Approval of Other Uses of Phosphogypsum: Supporting Documents" web page and have been unsuccessful in identifying any such document. Thank you in advance for your time and consideration.

Respectfully,
Audrey Ford

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 9/23/2020 8:13:31 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: RE: TFI Final Comms Plan & Press Release--Link to Web Page Attached.

Hi Tony,

Ex. 5 Deliberative Process (DP)

Thank you for all of your help and how quickly you were able to pull together the draft web page.

Ex. 5 Deliberative Process (DP)

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Wednesday, September 23, 2020 2:47 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: TFI Final Comms Plan & Press Release--Link to Web Page Attached.
Importance: High

Dear Stefanie:

Here is the link to the revised page:

Ex. 5 Deliberative Process (DP)

Tony Nesky
Center for Radiation Information and Outreach
Tel: 202-343-9597
nesky.tony@epa.gov

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, September 23, 2020 1:56 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: FW: TFI Final Comms Plan & Press Release

Tony,

I plan to discuss the attached at our 2PM meeting. Thank you for meeting with me ☺

From: Bacon, Stefanie
Sent: Monday, September 21, 2020 4:43 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: TFI Final Comms Plan & Press Release

Good afternoon,

Attached is the final TFI comms plan and press release. The attached items have been revised to incorporate feedback and comments from Charles Starrs. Please note that there are several placeholders in the comms plan. I have confirmed with OAR comms that this is an acceptable practice, and the placeholders can be finalized once the Administrator issues the approval.

Please advise when these materials can also be forwarded (as final documents) to OAR comms.

Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/15/2020 6:26:29 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: INTERNAL ONLY Q&A
Attachments: TFI Communications Plan_RPD ONLY Q&A.docx

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 9/23/2020 5:56:11 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: FW: TFI Final Comms Plan & Press Release
Attachments: TFI response-Comms Plan_09 21 2020 .docx; TFI response-Press Release_09 21 2020 .docx

Tony,

I plan to discuss the attached at our 2PM meeting. Thank you for meeting with me ☺

From: Bacon, Stefanie
Sent: Monday, September 21, 2020 4:43 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: TFI Final Comms Plan & Press Release

Good afternoon,

Attached is the final TFI comms plan and press release. Ex. 5 Deliberative Process (DP) Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 8/25/2020 12:53:14 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: Bacon, Stefanie shared "TFI Communications Plan_8-21 jw" with you.

This is a link to the TFI Comms plan.

Ex. 5 Deliberative Process (DP)

Microsoft OneDrive

Microsoft respects your privacy. To learn more, please read our Privacy Statement.
Microsoft Corporation, One Microsoft Way, Redmond, WA 98052

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 11/4/2020 6:57:20 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
CC: Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: The Sun Media Inquiry

Good afternoon Dan,

I have not heard anything from Charles after sending RPD's revised media inquiry responses this morning, or a reminder follow-up email this afternoon. Are you comfortable with me sending the responses approved by Lee (and pasted below) to Kati as final without any further OGC input?

1. Are the underlying assumptions of risk of death due to radiation exposure based on studies of atomic bomb survivors? If not, where do they get the risk of fatal cancer numbers from?

Ex. 5 Deliberative Process (DP)

2. Why did the EPA not allow for public comment on this rule change? When is public comment required?

Ex. 5 Deliberative Process (DP)

3. By government road projects, does this mean just those with federal funding? Not state or local funding?

Ex. 5 Deliberative Process (DP)

4. Will these applications to the EPA come from the phosphate manufacturers or the governmental entity that wants to use the material in road building?

Ex. 5 Deliberative Process (DP)

5. Has the EPA received any applications yet?

Ex. 5 Deliberative Process (DP)

6. How much of an impact can the EPA estimate have on the problem of gypstack formation? Will manufacturers be taking directly off their existing stack or from new material being generated by the manufacturing plants?

Ex. 5 Deliberative Process (DP)

7. how does the EPA estimate the lifetime risk of exposure to the stacks? This is important because the EPA said the relative risk was the same.

Ex. 5 Deliberative Process (DP)

Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 9/14/2020 5:16:28 PM
To: Veal, Lee [Veal.Lee@epa.gov]
CC: Wieder, Jessica [Wieder.Jessica@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: TFI Comms Plan & Press Release
Attachments: TFI Press Release_9-14.docx

All:

I have passed the comms materials forward to Kati Stevens. She would like to see them again once they are approved by ORIA management.

Ex. 5 Deliberative Process (DP)

Thanks!
Stefanie

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, September 14, 2020 12:15 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: TFI Comms Plan & Press Release

Hi Stef,

I don't have any further changes. Do you want to send the two external documents forward to comms for their review?

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, September 11, 2020 3:15 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: TFI Comms Plan & Press Release

Good afternoon Lee,

Attached please find draft versions of the TFI Communications Plan and TFI Press Release. These documents have been reviewed by Jessica, Tom & Dan.

Ex. 5 Deliberative Process (DP)

Please let me know if you have any questions,
Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 8/21/2020 8:39:31 PM
To: Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: Draft TFI Comms Plan
Attachments: TFI Communications Plan_8-21.docx

Hi Jess,

Attached is the draft TFI Comms Plan.

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Please let me know if you have any questions. I look forward to hearing your feedback ☺

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 12/2/2020 4:23:36 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]
Subject: FW: EPA tech summary errata
Attachments: EPA-HQ-OAR-2020-0442-0018.pdf

Joe,

Do you have the word version of this document? I looked for it on SharePoint and I found a document that seemed like it was the right title, but when I opened it, the document contained no content.

Ex. 5 Deliberative Process (DP)

Thanks!
Stefanie

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Monday, November 30, 2020 10:26 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: EPA tech summary errata

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 9/14/2020 5:04:51 PM
To: Stevens, Katherine [stevens.katherine@epa.gov]
CC: Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: TFI Comms Plan & Press Release
Attachments: TFI Communications Plan_9-11-20.docx; TFI Press Release_9-11.docx

Good afternoon Kati,

Attached please find our TFI Communications Plan and TFI Press Release. These documents have been reviewed by our RPD management and have been (or will shortly be) passed along to ORIA management for review.

Please let me know if you have any questions,
Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 11/4/2020 1:27:06 PM
To: Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: RE: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

I'm going to run the answers through Charles one more time to make sure he sees no red flags. Then get it over to Kati.

From: Wieder, Jessica <Wieder.Jessica@epa.gov>
Sent: Wednesday, November 4, 2020 8:26 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: Re: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

What is left to do on this?

Jessica Wieder
Director, Center for Radiation Information and Outreach
U.S. Environmental Protection Agency
Radiation Protection Program
w: 202-343-9201
c: 202-420-9353

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, November 4, 2020 8:17 AM
To: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

Thanks Jess ☺ I appreciate that you took the time to send this email. Hopefully, we can get the responses out on this inquiry later this morning. I have been in contact with Kati to let her know our timeline.

From: Wieder, Jessica <Wieder.Jessica@epa.gov>
Sent: Tuesday, November 3, 2020 5:53 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: Re: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

Ex. 5 Deliberative Process (DP)

You did well navigating through all the input today.

Jess

Sent from my iPhone

> On Nov 3, 2020, at 4:27 PM, Bacon, Stefanie <Bacon.stefanie@epa.gov> wrote:
>
> Team,

There have been a lot of emails today about The Sun's media request. I have compiled the most up to date versions of all answers that I've seen to date. Please review the answers to all questions below and let me know if any changes are needed.

Thank you,
Stefanie

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/15/2020 4:18:49 PM
To: Diaz, Charlene [diaz.charlene@epa.gov]
Subject: RE: EPA Press Release on Approval of Other Use for Phosphogypsum
Attachments: TFI response-Comms Plan_09 21 2020 .docx

Yes, sorry, I have been on calls since we got off of our morning TFI call. The comms plan is attached. Within the comms plan is an extensive Q&A. I leave it up to you if you prefer to pass along the comms plan in full, or if you just want to snip out the Q&A and send that.

From: Diaz, Charlene <diaz.charlene@epa.gov>
Sent: Thursday, October 15, 2020 12:08 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: EPA Press Release on Approval of Other Use for Phosphogypsum

Hi Stefanie,

Will you please provide the document you wanted me to share with the Regions; in addition to the link to the Press Release.

Thanks☺
Charlene

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator
Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, October 15, 2020 8:13 AM
To: Diaz, Charlene <diaz.charlene@epa.gov>
Subject: Re: EPA Press Release on Approval of Other Use for Phosphogypsum

Thank you Charlene!

Sent from my iPhone

On Oct 15, 2020, at 7:32 AM, Diaz, Charlene <diaz.charlene@epa.gov> wrote:

Hi Stefanie,

I will send out the press release.

Jon, please keep in mind that we have a special guest on the call Tuesday, Kathy Held from NRCP. I have only alloted about 15 minutes for roll cal and updates,

Thanks,
Charlene

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator
Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, October 14, 2020 4:55 PM
To: Diaz, Charlene <diaz.charlene@epa.gov>
Cc: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: FW: EPA Press Release on Approval of Other Use for Phosphogypsum

Charlene,

Lee asked if you could please provide the TFI press release below to the regional contacts tomorrow AM (10/15). Lee also expects that this will be discussed on Tuesday's call.

Jon, would you be available to speak for about 10 min on the Tuesday call to provide an update on TFI and today's action?

Thanks!
Stefanie

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Wednesday, October 14, 2020 4:34 PM
To: Starrs, Charles <Starrs.Charles@epa.gov>; Edwards, Jonathan <Edwards.Jonathan@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Cc: OAR-ORIA-RPD <OARORIARPD@epa.gov>
Subject: EPA Press Release on Approval of Other Use for Phosphogypsum

https://www.epa.gov/newsreleases/epa-approves-use-phosphogypsum-road-construction

Tony Nesky

Center for Radiation Information and Outreach
Tel: 202-343-9597
nesky.tony@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 9/11/2020 5:37:51 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: TFI Draft Press Release

Thank you Dan & Tom,

I have accepted your edits, they were all very straightforward and I appreciate you taking the time to review and further clarify the document.

Should I send this to Lee for review, or would you like to include it as an attachment when you send the comms plan forward?

Thanks,
Stefanie

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Friday, September 11, 2020 1:31 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: TFI Draft Press Release

I have added some.

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, September 11, 2020 11:50 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: TFI Draft Press Release

Hi Everyone,

I would like to move the TFI Press Release forward. If you have any comments please add them by COB today. I will review and incorporate any comments (including the ones Tom has left) on Monday.

Thanks!
Stefanie

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, September 9, 2020 8:35 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: TFI Draft Press Release

Stefanie,
I think it is a good press release, but I have some edits.

Tom Peake

US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, September 09, 2020 8:00 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Subject: TFI Draft Press Release

Good morning,

I have worked with Jess to draft a TFI press release. The draft is uploaded to SharePoint:

Ex. 5 Deliberative Process (DP)

Please review and provide any comments.

Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 11/3/2020 9:36:22 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

Thanks Dan ☺

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Tuesday, November 3, 2020 4:36 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Hellberg, Dennis <Hellberg.Dennis@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; Boyd, Mike <Boyd.Mike@epa.gov>
Subject: RE: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

I have no changes. Thanks.

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, November 03, 2020 4:27 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Hellberg, Dennis <Hellberg.Dennis@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; Boyd, Mike <Boyd.Mike@epa.gov>
Subject: FOR REVIEW | Afternoon Draft Answers to The Sun's Media Inquiry

Team,

There have been a lot of emails today about The Sun's media request. I have compiled the most up to date versions of all answers that I've seen to date. Please review the answers to all questions below and let me know if any changes are needed.

Thank you,
Stefanie

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/27/2020 7:17:24 PM
To: Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: TFI Media Tracker
Attachments: TFI Media tracker.xlsx

Jess,

Attached is the updated TFI media tracker. 10 new published articles have been added. The tone of the articles has shifted. Previously there was neutral to negative coverage, and as of today, coverage has shifted to primarily negative coverage with a focus on concern for public health. The only exception is one article that covered Administrator Wheeler's visit to Mosaic.

Please let me know if you have any questions or edits. I will send this to Lee before the end of the day.

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 12/6/2019 3:08:32 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: RE: For Review: Draft TFI Webpage

Ok, fantastic, thanks for the update. I look forward to hearing what management decides on webpage and/or FR NOA.

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Friday, December 6, 2019 10:06 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: For Review: Draft TFI Webpage

Thanks, this looks really good.

Ex. 5 Deliberative Process (DP)

- Jon

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, December 05, 2019 2:33 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: For Review: Draft TFI Webpage

Jon:

I provided the draft TFI webpage to Jessica for initial feedback. She had some very good comments. There were only two comments that I couldn't resolve. Could you please see the document in the location below, and address the comments tagged to you?

Ex. 5 Deliberative Process (DP)

Once you've had a chance to review this can go to Dan & Tom.

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 12/5/2019 7:33:44 PM
To: Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: RE: Draft TFI/Phosphogypsum Web Page

Thank you Jess, these were fantastic comments!

I've resolved most of the comments, and asked Jon to review two comments that I couldn't resolve. Once Jon looks at it, the draft will go to Dan & Tom for review.

Thank you again for looking at this, especially while you are out of the office!
Stefanie

From: Wieder, Jessica <Wieder.Jessica@epa.gov>
Sent: Wednesday, December 4, 2019 8:18 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Draft TFI/Phosphogypsum Web Page

Hi Stefanie – This is a great first draft. I have some questions and comments in the attached document to help get it ready for posting with the FR Notice. A lot of the TFI-specific language will be great to have when a decision is made.

Great work.

Jess

Jessica Wieder
Director, Center for Radiation Information and Outreach
U.S. Environmental Protection Agency
Radiation Protection Program
w: 202-343-9201
c: 202-420-9353

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Wednesday, December 04, 2019 12:18 PM
To: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: Draft TFI/Phosphogypsum Web Page

Jess,

Attached is a draft template and content for the TFI phosphogypsum webpage. I am providing a preview to you before sending up to Tom and Dan. Please let me know if there are any show stoppers ☺.

Ex. 5 Deliberative Process (DP)

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency

Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/19/2020 8:44:42 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: FW: TFI Media Tracker
Attachments: TFI Media tracker.xlsx

+TFI Team for awareness.

From: Bacon, Stefanie
Sent: Monday, October 19, 2020 4:34 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: TFI Media Tracker

Good afternoon Lee,

Attached is a simple spreadsheet listing various outlets that have covered the TFI action since EPA's press released was announced last Wednesday. The attached only covers traditional media, and not social media. Jessica has seen the attached and asked that I forward it to you.

About half the sources cover the announcement and include an angle (e.g., concern for public health/environment) while approximately half of the sources just share the announcement without any angle. So, I would say coverage is split approximately 50% negative, 50% neutral.

I hope this is helpful. Please let me know if you would like any changes made to the tracker, and when you might want an update on the media coverage.

Thanks,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 4/14/2020 6:31:14 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: Word Document Files for TFI Application
Attachments: Appendix 6 - Economic Report.docx; Appendix 7 - Location of PG Stacks.docx; Appendix 4a - Response to Jan 16 2020 Questions.docx

Not a problem, I converted them all yesterday – but unfortunately not all of the files attached to my email. Here's the document requested, along with the others that were missing.

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Tuesday, April 14, 2020 2:28 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Word Document Files for TFI Application

Ooops I apologize I meant to type convert to word from pdf.

-Joe

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, April 14, 2020 2:26 PM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: Word Document Files for TFI Application

4a was provided to us in PDF format from TFI. It's attached here if you need a copy.

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Tuesday, April 14, 2020 2:24 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Word Document Files for TFI Application

Hi Stefanie,

I had a request from Jay for the document 4a to be converted to pdf. Would you be able to send that to me?

Thanks,

Joe

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Monday, April 13, 2020 3:33 PM
To: Rustick, Joseph <rustick.joseph@epa.gov>

Cc: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: Word Document Files for TFI Application

Hi Joe,

To follow-up on our conversation from this morning, attached are the converted word document files from TFI's recently resubmitted application.

Hope these are helpful!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

MEMO

ARCADIS Design & Consultancy for natural and built assets

To:
Andy O'Hare
The Fertilizer Institute

Copies:

Arcadis Canada Inc.
121 Granton Drive, Suite 12
Richmond Hill, Ontario L4B 3N4
Tel 905 764 9380
Fax 905 764 9386
[HYPERLINK "http://www.arcadis.com/" \h]

From:
Douglas Chambers

Date:
April 7, 2020

ARCADIS Project No.:
30006877

ENVIRONMENT

Subject:
Response to EPA Questions issued on Jan 16, 2020

In response to a set of questions from the United States Environmental Protection Agency (USEPA), related to the risk assessment report submitted in October 2019[1] as support to the petition for beneficial use of phosphogypsum, Arcadis has prepared the following responses and comments.

For each paragraph provided by EPA in their questions, Arcadis has provided a response. Where a full response could not be included in this memo, reference to additional information is provided.

Modeling approach:

1. USEPA: The developers of the risk assessment chose to use a deterministic (vs. stochastic) model using discrete input parameters judged to be typical. From the standpoint of model development, this was a simpler—and potentially clearer—approach. However, a probabilistic approach to model input parameters could have provided the opportunity to incorporate uncertainty and variability into the model, and also could have explicitly included other road designs or variations on road design.

Arcadis: Arcadis intentionally chose a deterministic approach as a full probabilistic approach is quite challenging to present to the public. We recognize that there are variations in scenarios and assumptions and therefore, we intentionally made assumptions and selected parameters that in our view overestimate the potential exposures and doses bracketing the risk. Moreover, the models are linear for key parameters, such as Ra-226 concentration and exposure duration and hence readily scalable. In addition, we believe that the current approach estimates a reasonable maximum exposure (RME).

The RME scenario considers the highest exposure that might reasonably be expected to occur, one that is well above the average case of exposure but within the range of possibility and is intended to provide the basis for estimating the maximum individual risk (MIR). Use of the RME to model baseline human health risks is a conservative approach, in that it yields upper-bound cancer risk and non-cancer hazard estimates (USEPA, 1989). The "intent of the RME is to estimate a conservative exposure case (i.e., well

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[1] Arcadis 2019. *Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum*, Report to The Fertilizer Institute, October.

above the average case) that is still within the range of possible exposures."[2] Each exposure factor used to estimate the RME should be selected "so that the resulting estimate of exposure is consistent with the higher end of the range of plausible exposures" (citing EPA 1991 guidance).[3]

A National Academy of Science (NAS) Committee reviewing EPA's regulation of technologically enhanced naturally occurring radioactive material (TENORM) recommended that EPA "should use exposure and dose risk assessments that are "reasonably realistic"" in developing standards for exposure to the various types of low level naturally occurring radiation.[4] "The Committee defined "reasonably realistic" as "not … .intended to greatly overestimate or underestimate actual effects for the exposure situation of concern."" and EPA agreed with the Committee's recommendations.[5] The use of reasonable exposure assumptions is supported by the courts, which have long held that exposure assumptions used "must bear some rational relationship" to the actual conditions, and disallowed unduly conservative approaches.[6]

The current deterministic approach of the Risk Assessment focusing on RME scenarios to estimate MIR, provides the best alignment with the purpose of the RA, to compare predicted risks from the proposed use of PG against the risk threshold that is consistent with the determination of a 'safe' level. Overall, the choice of parameters other than those used in the current risk assessment are more likely than not to result in lower doses and risks to the receptor.

Probabilistic (stochastic) approaches would provide added information of the potential variability and uncertainty of the risk at lower risk levels, but overall would not change MIR substantially. In addition, the

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[2] EPA, EPA: Risk Assessment Guidance for Superfund: Volume III - Part A, Process for Conducting Probabilistic Risk Assessment, 7-1 (2001), *available at* [HYPERLINK "https://www.epa.gov/sites/production/files/2015-09/documents/rags3adt_complete.pdf" \h] [HYPERLINK "https://www.epa.gov/sites/production/files/2015-09/documents/rags3adt_complete.pdf" \h] See also Interstate Technology Regulatory Council, Decision Making at Contaminated Sites, Issues and Options in Human Health Risk Assessment at 6.1.1 (2015), *available at* [HYPERLINK "https://www.itrcweb.org/risk-3/Default.htm" \l "6.%20Exposure%20Assessment.htm" \h] [HYPERLINK "https://www.itrcweb.org/risk-3/Default.htm" \l "6.%20Exposure%20Assessment.htm" \h] [HYPERLINK "https://www.itrcweb.org/risk-3/Default.htm" \l "6.%20Exposure%20Assessment.htm" \h] [HYPERLINK "https://www.itrcweb.org/risk-3/Default.htm" \l "6.%20Exposure%20Assessment.htm" \h](ITRC, Decision Making at Contaminated Sites), citing EPA Guidance, which states that "[t]he RME . . . can be defined as "the maximum exposure that is reasonably expected to occur within a potentially exposed population."

[3] Id.

[4] EPA, Report to Congress, Evaluation of EPA's Guidelines for Exposures to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), 15 (June 2000) (describing a National Academy of Sciences report on TENORM), available at https://[HYPERLINK "http://www.epa.gov/sites/production/files/2015-" \h] 04/documents/402-r-00-001.pdf (EPA Report to Congress Re: TENORM).

[5] Id.

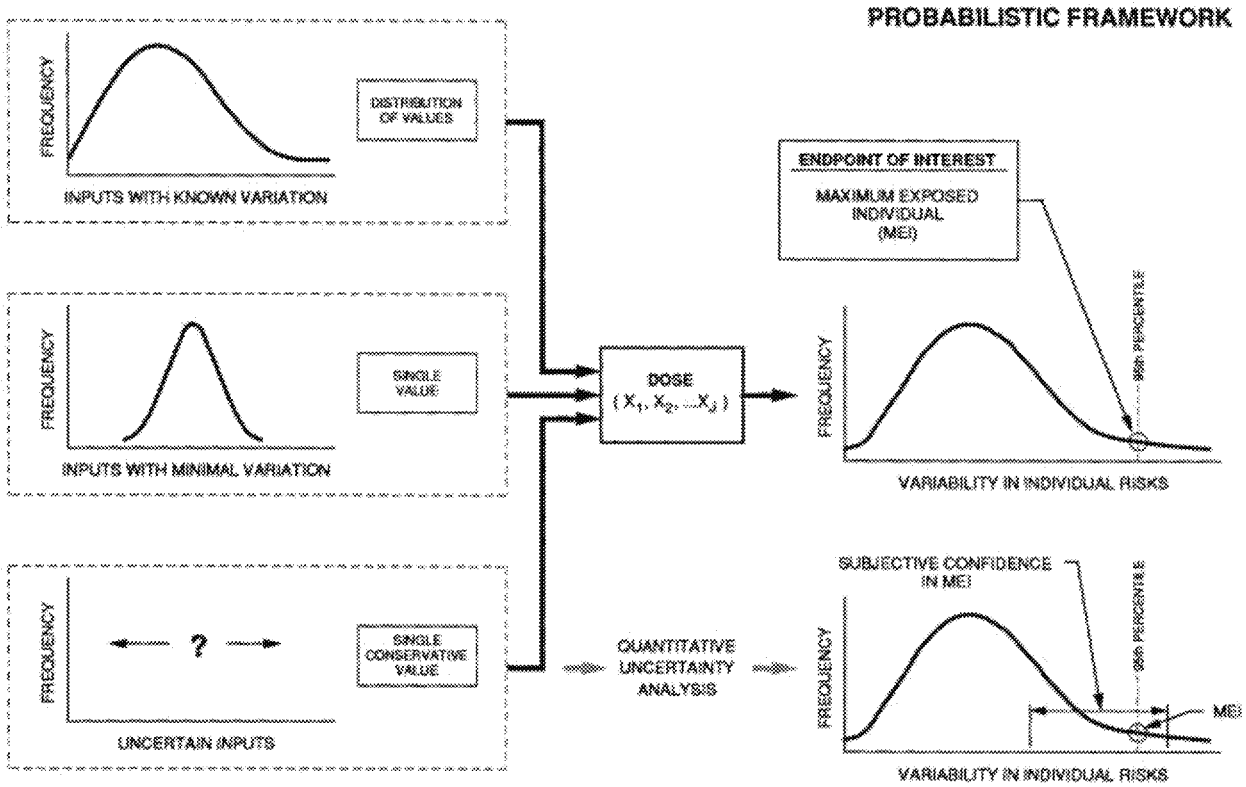
[6] *Leather Indus. of America v. EPA*, 40 F.3d 392, 405 (D.C. Cir. 1994).

complexity of developing subjective probability distribution functions for the model parameters can be quite difficult and often challenging to explain to the general public and thus the probabilistic approach was not selected for the assessment. The modelling approach using deterministic parameters to calculate RME dose and risk estimates was reviewed with EPA in advance of the Risk Assessment.

To illustrate the possible output of a probabilistic approach Figure 1.1 is provided below. The deterministic approach targets calculations for the Maximum Exposed Individual (MEI) or person in the RME scenario, often someone at the upper-end (approximately 90th to 95th percentile) of dose (risk). EPA guidelines state that the assessor may derive a high-end estimate of exposure by using maximum or near maximum values for one or more sensitive exposure factors, leaving others at their mean value.[7] Based on our experience with regulatory decisions, the MIR from a deterministic assessment as performed in our October 2019 risk assessment would be generally comparable to these upper limits of dose (risk).

FIGURE 1.1

PROBABILISTIC FRAMEWORK



[7] Exposure Factors Handbook: 2011 Edition at (2011) [HYPERLINK "https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252" \h]

2. USEPA: 61.206(b)(8) requires the risk assessment to include an estimate of the risk distribution.

Arcadis: The original NESHAPS (December 15, 1989 Federal Register) defines a risk distribution estimate as how many persons within a certain distance (e.g. 80 km) of a source of pollutant emissions are at an increased level of individual risk. This requires an estimate of the dispersion of a radioactive pollutant, from a source and an estimate of the population within that distance.

EPA clarified at our meeting that providing more risk distribution information was information on how the risk varied with the "variation of the geometry of exposure" and with different exposure time frames. The RME approach utilized in the risk assessment also serves as a reasonable upper bound on the risk distribution and is a readily accepted approach for not only representing the maximum exposures but also providing insight into risks to people who might be exposed to PG. RMEs are constructed to likely overestimate risks for highest exposure situations; actual risks to these people and risks to the rest of the population would all be lower. Knowledge is relied upon for setting such bounds for the RME and when bounded values are used in calculation, the results are conservative (i.e., higher) estimates of the risks.

Although risk distribution was used in 1989, many EPA risk assessments (including the 1992 BID risk assessment) do not utilize risk distribution. The general risk distribution discussed below is acceptable in this situation.

The radiological "pollutants" associated with PG in roads are direct gamma emissions, particulates, and radon. As shown in the risk assessment, external gamma is by far the dominant source of dose, followed by radioactive particulate emissions and radon.

The gamma exposure dose decreases rapidly with distance, for example at one road used in a Florida Institute of Phosphate Research (FIPR) study, the exposure was indistinguishable from background levels at 50 feet from the road centerline (FIPR, 1989[8]). For the nearby residential exposure scenario, the risk calculated in the October 2019 radiological risk assessment calculated that radiological exposure is always below background levels and reduces with distance from the road, becoming indistinguishable from the variability of background at 50 feet from the road's edge.

Background terrestrial radiation has been shown to have wide variability between states and within states in the US (S. Cohen & Associates 2005)[9].

> *It is instructive to note that not only are there substantially large differences in the average terrestrial doses among states (e.g., 14.3 mrem/yr in Florida versus 42.6 in Colorado), but there are also large differences in the average terrestrial dose rates among cities within a state. For example, in Colorado, the average terrestrial dose rate in Pueblo is 29.2 mrem/yr, while in Denver it is 57.4 mrem/yr. In Las Vegas, Nevada, the terrestrial dose rate is 12.7 mrem/yr, while in non-urban regions of Nevada it is 29.2 mrem/yr.*

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[8] Chang, Wen F., Chin, David A., and Ho, Robert, 1989. Phosphogypsum For Secondary Road Construction, University of Miami, For Florida Institute of Phosphate Research, Publication No. 01-033-077, 01-041-077.

[9] S. Cohen & Associates. 2005. Assessment of Variations in Radiation Exposure in the United States Contract Number EP-D-05-002 Work Assignment No. 1-03. Prepared for U.S. Environmental Protection Agency Office of Radiation and Indoor Air 1310 L Street, N.W. Washington, DC 20005.

The USNRP in Report No. 160[10] confirms the range of background terrestrial radiation dose in the USA is variable, depending on local geology and other factors, and ranges from about 10 mrem/y to more than about 40 mrem/y.

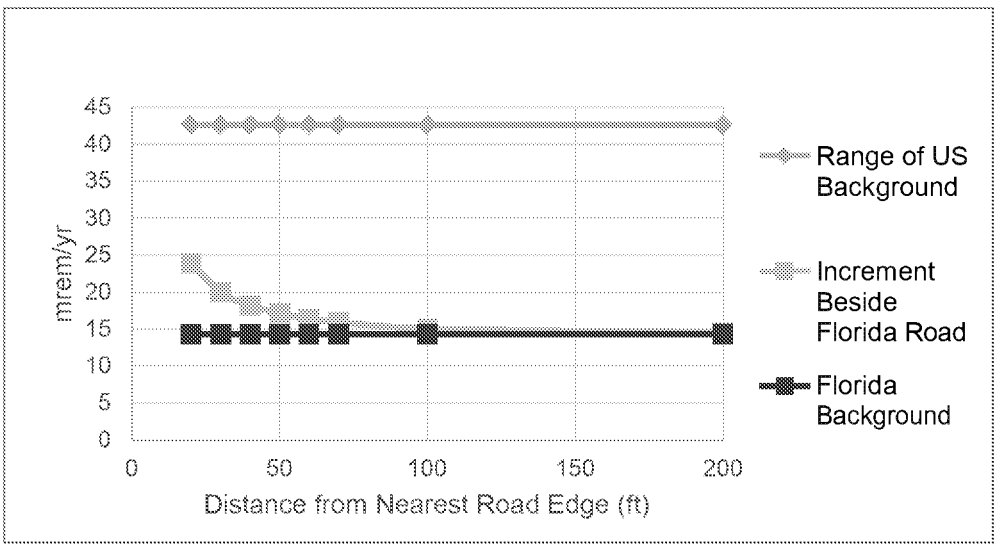
Figure 2 below combines the (notional) background radiation dose in Florida with the incremental dose from a PG road. The figure also displays the upper range of background radiation dose in the US (for Colorado). This clearly shows that dose from a PG road is inconsequential relative to background for distances typical for the closest residence. Further it shows that at distances reasonable for a second closest residence (approximately 100 feet) the dose is essentially zero.

These distances are well short of the 80 km values used in the 1989 risk distribution. Therefore, the contribution to a risk distribution is zero beyond that distance.

Similarly, it was shown in the Risk Assessment that the dose from inhalation and ingestion of particulates was also quite low, less than 10% of the total dose for the worker in the center of the road. As particulate concentration is highest on the road in the construction zone, particulate concentrations reduce with distance from the road and will quickly reach background levels again resulting in zero dose contribution to the risk distribution. In addition, particulate generation is only relevant during construction which occurs for a limited duration in any one location.

Last, is the radon generated from the road. Outdoor radon is quickly disbursed to background levels within a few tens of feet from the road, see for example the measurements on roads constructed with PG. (FIPR, 1989, "Phosphogypsum for Secondary Road Construction"). As previous, the calculated contribution to the risk distribution from radon is zero.

Figure 1 – Incremental External Gamma Dose with Distance Compared to Terrestrial Background



[10] NCRP Report No. 160, Ionizing Radiation Exposure of the Population of the United States

The following table provides summary comments on risk distributions by exposure pathway. The table explains the limited applicability of the RME scenario and the potential for lower exposures and doses to occur for a broader population.

SUMMARY OF RISK DISTRIBUTION FROM USE OF PG IN ROAD CONSTRUCTION		
Exposure Scenarios	RME (small number of people)	Potential Lower Exposures and Risk Distribution
Road Construction Worker	Risk: 0.5 in 10,000 Few if any workers would fit the RME assumption of 100% of workdays on the uncovered road base. The RME worker is exposed to less than 7% of background levels (for all members of the public.	Much less than 0.5 in 10,000 Most workers are expected to spend less than 100% of the workday on the uncovered road base. Dose and risk reduce linearly with reduced exposure time. Time on a covered road base was shown in the Risk Assessment to be a factor of 5 lower. The dose would range down to essentially zero for management and supervision who would spend very limited time on the road and out of vehicles. The number of workers in a road crew is estimated to be as small as 6 – 8 workers, which limits the risk distribution to a small group.
Road User	Risk: 0.1 in 10,000 This RME is assumed to be a heavy user of the road spending 2 hours daily on the road. This scenario is unlikely to occur until far into the future if PG roads become widely available. Until then it is unlikely a commuter would be able to spend this amount of time on a PG road. In the extreme case, the RME road user is exposed to less than 0.3% of background.	Well below 0.1 in 10,000 Most road users will be on the road for much less than two hours per day. Dose and risk reduce linearly with reduced exposure time. Initially when PG use in roads is newly implemented the availability of PG roads will be low reducing the opportunity to have substantive usage time. As the total amount of PG roads increase the risk distribution would increase with additional road users and cumulative usage time. The overall risk to an individual however, is not expected to exceed the RME estimates. Most road users would still have limited time on PG roads and this results in a proportionally limited dose and risk. The overall number of road users is difficult to specify as it depends on several factors including

		the road type and location relative to populated areas. However, the dose to road users would remain a small fraction of that from unavoidable background radiation.
Truck Driver	Risk: 0.5 in 10,000 The Truck Driver RME is limited to workers who participate in PG road construction projects. The assumptions for this scenario are set to estimate the upper end of likely dose and risk for this work. The RME Truck Driver is exposed to less than 6% of background levels.	A truck driver that has less than an RME exposure has lower risk than 0.5 in 10,000. There are a limited number of truck drivers involved in a road construction project. In addition, truck drivers will support numerous construction projects during the course of a year and many not involving use of PG. This limits the risk distribution for this exposure pathway to a relatively small number of people. In many cases, Truck Drivers will not work on PG road construction as much as assumed for the RME, resulting in a lower dose and risk.
Nearby Resident	Risk: 0.08 in 10,000 The Nearby Resident RME is based on extreme assumptions that are unlikely to apply to all residents of a PG road. The assumptions include close exposure to the road and long durations of residency throughout the exposure period. Based on these assumptions the Nearby Resident RME is exposed to 0.2% of background levels.	Most residents near a PG road would be exposed to much lower doses and risk, well below 0.08 in 10,000. Radiation levels from a PG road decrease rapidly with distance from the road and become indistinguishable from background at 50' to 100'. See figure and discussion. As a result, most residents immediately beside a PG road would be exposed to much less than the RME risk level, and residents beyond the immediately adjacent properties would experience essentially zero incremental risk. The overall risk distribution would depend on the overall length of the PG road and population density along the road but is limited to only those locations immediately beside the PG road.
Utility Worker	Risk: 0.004 in 10,000 The Utility Worker RME scenario represents an extreme case where a worker needs to disrupt the road for road or utility maintenance. The assumptions use worst case conditions to estimate the risks	Most Utility Workers would be exposed to risk much less than 0.004 in 10,000. Most utility repair requirements would involve exposure scenarios below those assumed for the RME conditions, due to smaller trenches and exposure areas, or shorter durations.

	and are limited to workers in a trench in a PG road and meeting the other exposure assumptions. The RME Utility Worker is exposed to approximately 0.3% of background levels.	The number of individuals entering a trench in a PG road is also limited based on the uniqueness of the work and the limited space. As a result, the risk distribution for the Utility Worker is limited to a small number of individuals.
Reclaimer Extreme Scenario	Reclaimer is an extreme scenario well beyond an RME assumption and therefore, is not appropriate to determine whether the use of PG is safe. This example for ultimate disposal was selected due to the use by EPA in 1992. Risk: 0.4 in 10,000 The Reclaimer would be exposed to approximately 1% of background levels. (total exposure of 78 mrem compared to a Background of 8,060 mrem over 26 years)	The Reclaimer scenario represents an extreme situation that is unlikely to even occur as described. As a result, the risk distribution is effectively zero. More realistic situations for the ultimate disposal of the road include continued use of the road as a road, or reuse of the PG road base for a new road, if the road was to be relocated or realigned. In the extreme case where a road is abandoned and then the land is reused for other purposes, the land preparation activities will realistically result in blending and mixing of the road base to levels that are indistinguishable from background levels. Overall, the risk distribution would be effectively zero.

In summary, the risk distribution from road construction is negligible, beyond the individuals who are on or immediately beside the road, as assessed in the Risk Assessment document.

3. USEPA: No discussion of uncertainty in model outputs is provided. There is no discussion of uncertainty around model input parameters, with the minor exception of uncertainty of the dose-to-risk conversion factor (p. 1-1). Except for briefly mentioning variability in naturally-occurring background radiation (p. 3-4), the risk assessment does not address variability around model parameters such as exposure factors, activity concentrations, exposure duration, etc.

Arcadis: The Risk Assessment was developed to examine a conceptual road design, to provide an estimate of the upper end RME risks associated with PG use in roads. It is impractical to perform a risk assessment that uses different values for every conceivable road design. Neither the 1989 nor the 1992 BID risk assessment considered every conceivable road design. Many features (such as the number lanes) do not affect the potential exposure. Many other road design features were set at an upper bound RME value and any design that uses different value will reduce the risk or not be an RME.

The following is an example list of factors utilized to minimize the impact of any uncertainties.

- We assumed that EPA's 1992 BID risk assessment used high end assumptions as was the policy at the time. In general, the 2019 radiological risk assessment is more conservative (i.e., results

in higher exposures) than the 1992 BID. The 2019 radiological risk assessment used the same exposure scenarios plus two new exposure scenarios.

- In conjunction with the submission of the Petition, TFI members agreed to perform radiological testing of PG. Nine PG stacks located in Central Florida (where the highest Ra-226 levels would be expected), Louisiana, and the Western U.S. with ten samples taken from each stack, for a total of 90 samples.4 A summary of the results is as follows:
    - The average Ra-226 concentration of all 90 samples is 18.6 pCi/g.
    - Ra-226 concentrations in individual samples range from 6.3 pCi/g to 27.9 pCi/g.
    - The average Ra-226 concentration from the 2019 stack sampling (18.6 pCi/g) is below the radioactivity concentration limit of 35 pCi/g proposed in the Petition, and well below the average Ra-226 concentration of 148 pCi/g that corresponds to an EPA safe risk level of 3 in 10,000.
    - No individual concentration from the 2019 stack sampling (with concentrations ranging from 6.32 pCi/g to 27.9 pCi/g) exceeds 35 pCi/g.
- The EPA 1992 BID assumed a 1:2 dilution of PG with soils for a road base concentration of 10 pCi/g. The October 2019 risk assessment utilized less dilution (1:1 PG:soil).
- The EPA 1992 BID assumed the road base was 0.25 m thick and 30 feet (9.15m) wide and that the road base is covered with a 0.12 m (5 in) thickness of asphalt. The October 2019 risk assessment utilized a road thickness of 0.25 m (the same as in 1992).
- The EPA 1992 BID assumed PG in a concrete road incorporates 15% PG by weight and 0.12 m thick (5 in) and 24 feet wide (7.32 m). The October 2019 reviewed road base design criteria and concluded 15% was a high-end criterion.
- The EPA 1992 BID used exposure to the critical population group member (nearby resident 100 m (i.e., 328 ft) from the edge of the road). The October 2019 radiological risk assessment calculates the radiation levels at 50 feet from the edge of the road.
- The current risk assessment assumes a worker moves around over the road surface and is exposed at the average of the gamma fields at the center and edge of the road, which is more reasonable than assuming a worker never moves for 5 years. The stationary worker is not realistic or reasonable, therefore it is not an RME.
- The 1992 EPA risk assessment used a 0.6 shielding for the road user, but rather than determine the degree to which vehicles have changed the amount of metal in the under carriage of cars, the current risk assessment takes no credit for shielding provided by the vehicle which however would provide some level of shielding which is a conservative assumption and could reasonably be considered.
- The current risk assessment considered two receptors beyond those considered in the 1992 BID (truck driver and utility worker).

Given the fact that each of the exposure assumptions are RME (including road design parameters), the uncertainty is addressed with the risk assessment without having to perform numerous risk calculations that will simply confirm the nature of the RMEs utilized. If EPA identifies any road design factors that increase the radiological risk and are RME, the Petitioners will evaluate it. In summary, as described in the first item under Modelling Approach above, the selection of deterministic parameters was done at the conservative end of the expected range of uncertainty, to provide calculations tending to overestimate expected results.

Conceptual road model:

4. USEPA: What is the generic composition (in more detail) of a road? For example, if road base is to be composed of a mixture of soil and PG, what are the ranges of composition of the soils to be used (e.g., organic carbon content, clay contents, moisture).

Arcadis: The Risk Assessment is intended to provide a conceptual exposure model of PG use in roads and is not linked to a specific road segment approval.

The selected example road was a four-lane county road with two lanes in each direction. This type of road is common in rural, suburban and urban settings and represents the type likely to be constructed by state and local governments who can employ PG during construction.

Choice of this road type permits evaluation of construction workers, nearby residents, bicyclists and motorists, and utility workers. The road dimensions are 15 m wide (about 12 feet [ft] per lane) and 100 m long (segment length) for modelling exposures. The thickness of the road base containing PG and road surface (i.e., pavement) are 0.25 m and 0.12 m respectively consistent with the EPA BID (1992).

The road base in the example road was selected to be PG mixed with in-situ soil, as it is the most probable choice to mix with PG. This soil would likely be used whether or not PG was used in the road base mix and is not considered as a risk variable. The soil-PG mixture will be compacted as part of the road construction process leading to high densities in the road base. Other site-specific soil parameters were not defined and are generally less important to the overall risk calculations. Specifically, carbon or clay content and moisture levels are not key factors in the risk determination (i.e., the radiation levels do not vary significantly based on these factors. Gamma ray attenuation for a fixed thickness of shielding is based on the density of the material being penetrated and to a lesser degree the chemical composition. The gamma source strength for a large slab of gamma emitting materials is proportional to the source strength (disintegrations per cc per sec) and inversely proportional to the mass attenuation coefficient[11]. The first term, source strength, can be rewritten as Bq/g x g/cc (pCi/g x g/cc). The second term, mass absorption coefficient is the linear attenuation coefficient divided by density. Both terms are dependent on density (i.e., g/cc or equivalent units). Thus, for practical purposes, the density of the source material is the key factor irrespective of the characteristics of the source material per se.

5. USEPA: What is the basis for limiting phosphogypsum to 50% in the road base? Is there a geotechnical reason, such that structural stability suffers at higher proportions? Is there an optimal range for durability? Alternatively, would administrative controls need to be put in place to maintain this limit during construction? Would an end-user need to address the administrative controls in a specific use request?

Arcadis: Available research on experimental roads reported PG:soil ratios in the range of 1:2 PG:Soil. The EPA in their 1992 BID used a 1:2 mix of PG:sand. This is also the PG ratio in the Polk and Columbia county roads[12] constructed with input on the design and testing of the roads from the University of Miami and the Bureau of Materials & Research, the Florida Department of Transportation.

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[11] Rockwell, Theodore, July 1956. "Reactor Shielding Manual". U.S. Atomic Energy Commission, First Edition.

[12] Chang, Wen F., and Mantell, Murray I., 1990. Engineering Properties and Construction Applications of Phosphogypsum, University of Miami, Phosphate Research Institute, ISBN No. 87024-328-4.

In a study by W.F. Chang et at (Chang, Wen F., Chin, David A., and Ho, Robert, 1989)[13], various ratios of PG to soil were studied. California Bearing Ratio CBR test were conducted on ratios of PG: sand ranging from 100% sand to 100% PG. The PG to sand mixtures showed all mixes had CBR values higher than sand or PG separately. Various radios of PG to soil were used in sections of an experimental road in Polk County Florida. The PG was rototilled into the soil to various depths, A portion was also covered by an asphalt coat. These studies indicate that there is no reason to limit the quantity of PG to be used in a road. The limiting factor would be the measured compressive strength and durability of the admixtures prior to their use in the road. Further studies could establish guidance on the range of PG to soil ratio allowed for various soil types. A 50:50 mixture of PG and local construction materials such as sand or soil is likely to be an overestimate of the actual mix

As noted in the figure below, road design parameters and specifications are better optimized at lower PG:soil ratios. To be conservative of potential risks, the risk assessment considered the upper end of likely reasonable mixture ratios. As stated in previous comments, this parameter provides a linear impact on the risk results. So, if alternate concentrations of PG are desirable, the risks can be easily extrapolated up or down from the existing calculations.

The amount of PG that would be used in a lane/mile of road base depends on many things such as: thickness of the road base, the percent PG in the road base, density of the PG, width of a "lane". In the end, the appropriate County, State or Federal road authority will have to approve the specifications of the road base used in the design. However, to illustrate the concept, consider a road where 1) lane width is 25 feet, 2) the maximum thickness of the road base mix is 12-inches, 3) the maximum percent PG in the road base is 50%, 4) the dry density/95% proctor can be based off the attached Figure 3.6 from Chang and Mantell 1990[14].

The Figure 3.6 Maximum density curve is based on a PG soil mix, it provides the highest density with PG at 1/6 of the mixture – which can then be extrapolated using the curve for a half/half mixture. Using this range yields a 95% proctor density of 1.9 to 1.98 grams/ cubic centimeter which converts to 118.6 to 123.6 lb/cubic ft.

That said, a 25 ft wide lane for one mile, would require about 3,900 to 4,100 tons of PG per mile, rounded to 4,000 tons/mile.

However, it is the concentration of Ra-226 in the road base that determines the gamma radiation levels. For example, a road with PG at 1/6 of the mixture as described above would have a Ra-226 concentration 3 times lower than the calculations provided in the 2019 risk assessment, and result in doses and risks 3 times lower. As previously indicated, the 2019 risk assessment assumed a 1:1 mix of PG and local soils. This is considered a reasonable upper bound for such a mixture and hence alternative mixtures will have lower concentrations of Ra-226 than were assessed in the 2019 risk assessment and hence, it follows that the doses and risks would also be lower.

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[13] Chang, Wen F., Chin, David A., and Ho, Robert, 1989. Phosphogypsum For Secondary Road Construction, University of Miami, For Florida Institute of Phosphate Research, Publication No. 01-033-077, 01-041-077.

[14] Chang, Wen F., and Mantell, Murray I., 1990. Engineering Properties and Construction Applications of Phosphogypsum, University of Miami, Phosphate Research Institute, ISBN No. 87024-328-4.

36 PHOSPHOGYPSUM

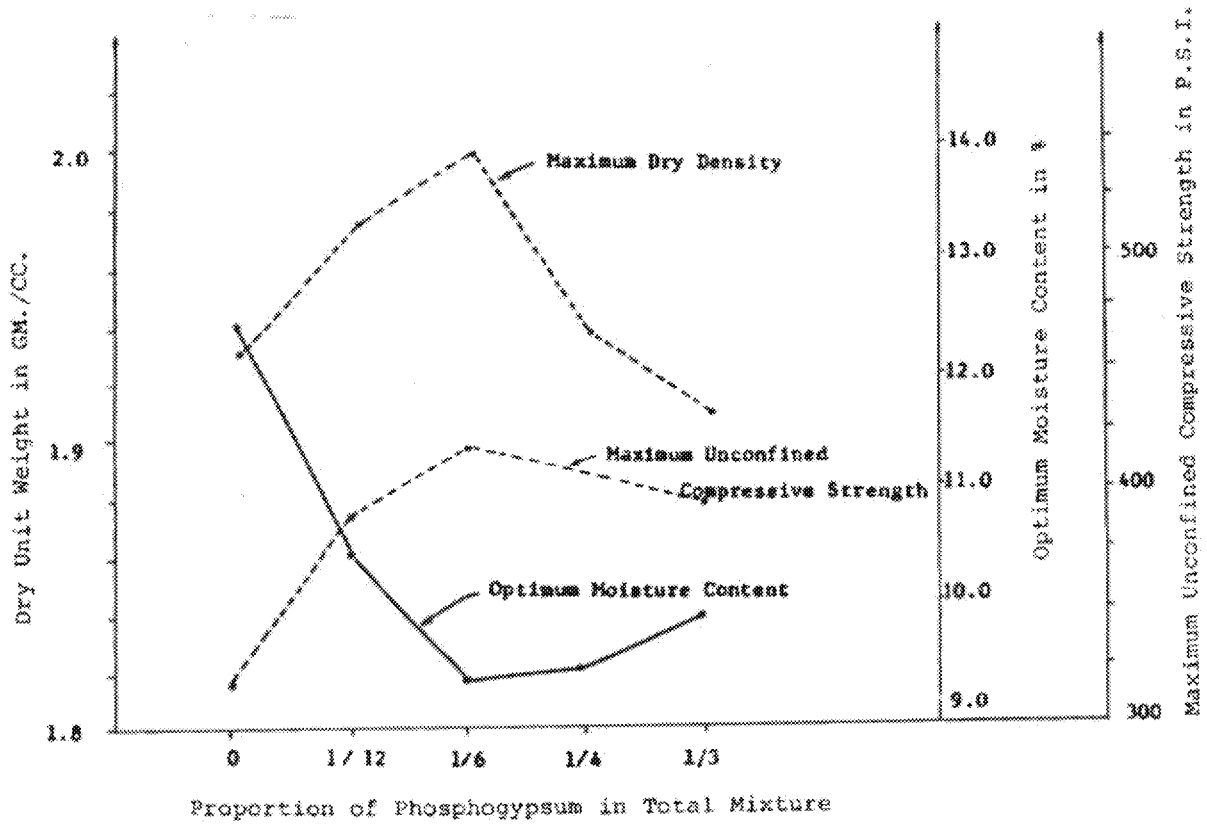

Figure 3.6 Variation in the maximum unconfined compressive strength, optimum moisture and maximum dry unit weight with change in the proportion of phosphogypsum in the various mixtures of clayey sand, sand and phosphogypsum.

6. USEPA: Reviewers had questions related to the conceptual model for the road design, specifically the restriction of the phosphogypsum-containing layer of road base to the area under the pavement. A road model used by the U.S. Federal Highway Administration, "Tech Brief: Bases and Subbases for Concrete Pavements," FHWA-HIF-16-005 (https[HYPERLINK "http://www.fhwa.dot.gov/pavement/concrete/pubs/hif16005.pdf)" \h].fh[HYPERLINK "http://www.fhwa.dot.gov/pavement/concrete/pubs/hif16005.pdf)" \h]shows a road base which extends 3 to 4 feet (91 to 122 cm) beyond the road cover on each side of the road. In this case, all scenarios would need to account for some gamma exposure from road base material that is not shielded by pavement, and the possibility that phosphogypsum may become airborne at the uncovered edges of the road base.

Arcadis: The risk assessment provided an examination of a conceptual road design with risks estimated for scenarios and exposure pathways expected to be the most dominant. The road design in the risk assessment approximated road design characteristics and plausible exposure scenarios for various types of roads. While some large highways may have exposed shoulders, those roads are unlikely to have pedestrians, cyclists or houses in close proximity. Suburban and urban roads represented a plausible

scenario which maximizes exposures for the dominant external gamma pathway. Airborne dust from exposed shoulders is not expected to be a dominant pathway due to the binding properties of PG and the limited potential for substantive intake. Further, road shoulders typically become infilled with vegetation which also suppresses dust.

To explore this question, Arcadis considered the dose and risk impacts for a conceptual road with a 4-foot uncovered shoulder. We estimated results that are not substantially different from that of the original conceptual design of a 15-meter-wide road. Consider the worst case a worker at the center of the road. Gamma rays emitted from the strip (consider the leading or close edge or 7.5 m from the center) would need to travel at an extreme angle (~7.6 degrees) to impact a worker at the center of the road at the dose point (one meter above the surface. From the far edge (8.7 m form the center) the angle is 6.6 degrees. Assuming gamma rays are emitted isotropically, then about 1% of the additional emitted gamma rays (1/90) strike the worker.

Additional gamma calculations were also done with RESRAD for an uncovered road shoulder as described below to confirm the above estimations. Two cases were run with all the parameters fixed with the exception of the area. The original area was 15 m by 100 m, the adjusted area was 17.5 m by 100 m. Table 1 presents the exposure for a worker at the road center in both cases. As indicated the maximum contribution to the dose is external gamma. The increase in dose for external gamma is about 1.5%

Table 1 Dose to a maximumly-exposed worker at the center of a road with constructed with PG

	Direct exposure mrem/year	Inhalation dose mrem/year	Inhalation Dose mrem/year	Total Dose mrem/year
Original Road (15 m x 100 m)	26.11	0.1423	1.918	28.170
Adjusted Road (17.5 m x 100 m)	26.51	0.1465	2.004	28.661
Increase %	1.5%	2.9%	4.4%	1.7%

A similar calculation can be performed with the exposure point at the edge with similar results. The conclusion is that the 3- to 4-foot (i.e., 1 m to 1.2 m) strip along the road has minimal increase in the dose and final risk.

7. USEPA: Are assumptions related to durability and weathering of roads based on documented experience? What are the assumptions regarding the frequency of repaving or other road maintenance/replacement? Are they correlated to the type of road and traffic projections? Would an end-user need to account for such assumptions in a specific use request?

Arcadis: Road maintenance related to weathering roads was not explicitly assessed in the 2019 risk assessment, nor was road maintenance assessed in the EPA 1992 BID. This scenario is not deemed to be an RME condition and would be bounded by risks calculated for the Road Construction Worker. Consequently, road type and traffic projections are not relevant to the risk assessment and would not need to be accounted for in a specific use request.

Potential doses arising from road maintenance are expected to be on the order of those from the Utility Worker scenario. Full repaving activities would be limited to exposures less than those arising from road construction.

Road maintenance is typically done by milling the surface, cleaning, applying tackifier (to assist in binding new asphalt to the underlying asphalt) and new asphalt, leading to minimal disruption of the road base (the PG containing layer). Section 10.5.3 of IAEA 78 Safety Report Series[15] provides several observations on use of PG for road base and suggests PG roads would require less frequent maintenance as compared to roads constructed with other clay-based and limestone materials.

> *Phosphogypsum has successfully been used as a binder for base course mixtures. Phosphogypsum based mixtures are more workable than clay based mixtures. Delays due to rain during construction are reduced because the compacted mixture does not absorb significant amounts of water. Shrinkage cracks and swelling, which often negatively affect the performance of clay based road beds, are greatly reduced. The stability of compacted phosphogypsum mixtures is superior to that of clay mixtures [186] and there is evidence that the use of phosphogypsum, if correctly optimized, leads to a progressive strengthening of the road bed over time [214, 215].*

Further as regards maintenance to date experience indicates minimal maintenance.

> *In Florida, USA, two experimental roads were built in 1986–1987 using both dihydrate and hemihydrate forms of phosphogypsum [224, 225]. The results of the evaluations are reported in Refs [226–228]. It was concluded that phosphogypsum, when subjected to optimum mixing and compaction, could be transformed into a solid of high strength that is effective as a binder to stabilize on-site soil. Phosphogypsum and sand mixtures, stabilized with a small amount of cement, possessed a load bearing capacity higher than that of locally mined limestone, which was at that time the material of choice for road bases in the region. It was also demonstrated that the incorporation of phosphogypsum into a cement based mixture for making 'roller compacted concrete' (a form of concrete widely used for road construction) led to improved compaction and strength properties [229]. The road bed described in Ref. [224] is shown in Fig. 49, which shows the condition after 25 years of use. The picture was taken during routine resurfacing. While the phosphogypsum is clearly not mixed in fully with other road bed materials, it has, nevertheless, lost none of its load bearing strength. As a result, the only maintenance requirement was a new layer of asphalt.*

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[15] International Atomic Energy Agency (IAEA) 2013. *Radiation protection and management of norm residues in the phosphate.* Vienna. (Safety reports series, ISSN 1020–6450; No. 78) STI/PUB/1582.

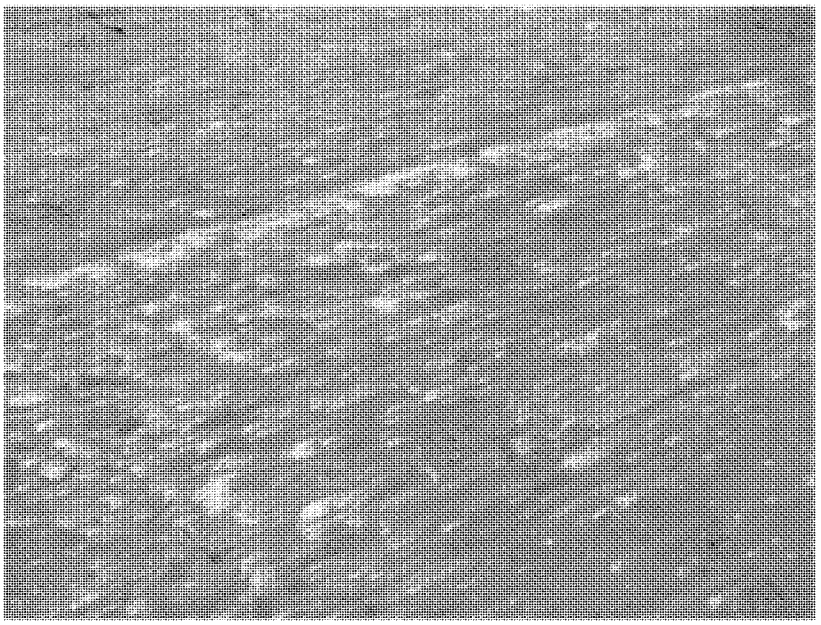

FIG. 49. Experimental road bed in Florida, USA, incorporating phosphogypsum (courtesy: Florida Industrial and Phosphate Research Institute).

In summary, the dose and risk from repairs conceptually cannot be greater than the dose and risk from the original road building since the PG is covered by concrete, asphalt or other material. The Risk Assessment provides the RME scenarios representing categories of exposure conditions with other minor exposure scenario representing lower risks. The example of road maintenance is not considered an RME and requires no further assessment.

Environmental and exposure pathways:

8. USEPA: The risk assessment would benefit from additional analysis of water pathways. Appendix 3 states that "Leaching to groundwater (or surface water) is likely not a complete exposure pathway for the petitioned PG reuse in road construction. This is because roadways are sloped to drain precipitation and paving will act as a barrier to infiltration through the compacted road base beneath. Despite this, literature regarding leaching and water quality was evaluated as part of this screening assessment (see the section titled "Leaching and Water Quality")." (p. 4) At least qualitative consideration should be given to direct contact with surface or groundwater due to flooding events, high water tables, and the presence of karst in phosphate lands. Likewise, reviewers suggested that the risk assessment consider the weathering of the road – will it develop fractures, potentially leading to infiltration resulting from road weathering cause leaching?

Arcadis: Previous risk assessments including 1992 Background Information Document for "Potential Uses of Phosphogypsum and Associated Risks", EPA 1992[16] and SENES 1997[17] examined the potential for impacts to groundwater and surface water pathways. These studies found no realistic potential for impacts to these pathways. Groundwater and surface water pathways were identified to be inconsequential by the EPA BID calculations. Radionuclides were not calculated to reach the nearby well water via the groundwater for almost 10,000 years. For off-site (more distant) wells and river water, radionuclides were not calculated to reach these waterbodies via groundwater for almost 100,000 years. The EPA BID reported in Note C, Table 4.15, that groundwater velocities and retardation factors in the modelling were the factors contributing to this result.

> *No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.*

Exploratory calculations were completed by SENES Consultants Limited (1997) (now Arcadis Canada Inc.) to review how EPA calculations for the Background Information Document (BID) and Final Rule. SENES reconstructed the BID calculations with nearly identical results as shown in Table A.1 from SENES 1997. With respect to water pathways, the results were consistent, showing that there was no impacts or very limited results, orders of magnitude below other pathways of interest, as shown in the table.

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[16] United States Environmental Protection Agency (USEPA) 1992. Potential Uses of Phosphogypsum and Associated Risks, Background Information Document. U.S. Environmental Protection Agency, Air and Radiation (ANR-459). EPA 402-R92-002. May.

[17] SENES Consultants Limited, 1997. Application for Exemption – For Use of PG in the Construction of Thornhill Road, Polk County Florida. Prepared for the Florida Institute of Phosphate Research (FIPR). Draft.

Table A.1

BID RECONSTRUCTION RESULTS
(Asphalt Road Constructed Using Phosphogypsum Containing Radium-226 At 26 pCi/g)

	Comparison of BID results and reconstructed results Dose, mrem per year (Lifetime risk per year of exposure)	
	BID Dose(Risk)	BID Reconstruction Dose(Risk)
Construction Worker - gamma no shielding from equipment - gamma with shielding from equipment - inhalation of dust - dry site - inhalation of dust - humid site	 41 (1.5×10^{-5}) 25 (9.0×10^{-6}) 2.5 (2.2×10^{-7}) 1.0 (8.4×10^{-8})	 42 (1.3×10^{-5}) 25 (7.6×10^{-6}) 2.5 (2.1×10^{-7}) 1.0 (8.6×10^{-8})
Person driving on road - gamma	 0.22 (8.2×10^{-8})	 0.23 (7.2×10^{-8})
Critical Population Group - gamma, 100 m off-site - ingestion of well water - ingestion of food	 0.043 (1.6×10^{-8}) —[a] —[a]	 $<1.0 \times 10^{-7}$ ($<1.0 \times 10^{-13}$)[a] 0.0037 (8.2×10^{-10})[b] —[b]
Off-site Individual - river water from groundwater - river water from surface runoff	 —[c] 0.02 (1.5×10^{-9})	 —[c] 0.02 (2.2×10^{-9})

Notes:

a. Critical Population Group gamma dose estimates are less than the stated values. These values were calculated in MicroShield without taking account of shielding provided by the upper layer of road material. Risks for this pathway are calculated based on a risk factor of approximately 3.9×10^{-7} $mrem^{-1}$ (EPA 1989). As MicroShield does not provide radionuclide-specific doses, this alternative approach to the risk calculation was utilized. For further information see Part II, Section 3.3.

b. The values stated for well water ingestion by the CPG correspond to year 10,000. No radionuclides were calculated to reach the well water in any of the prior years that were calculated. The food pathway for the CPG was not modelled as it is expected to have a similar result, or less, than the well water pathway. This is based on the BID assumption that food eaten by the CPG is irrigated with well water.

c. For these pathways, no radionuclides were calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

9. USEPA: Related to the question of whether interactions with ground and surface water are possible, if dissolution or leaching does take place, is there a potential for uptake and bioaccumulation by organisms of any of the radiological constituents of phosphogypsum?

Arcadis: As noted above, radiological groundwater and surface water impacts were not expected to be relevant in the overall risk determinations for this potential use of PG. By extension subsequent

pathways to groundwater and surface water were shown not to be relevant, as documented in BID 1992, Table 4-15 and SENES 1997, summarized in Table A.1 above.

Exposure scenarios/receptors:

10. USEPA: The risk assessment should address the handling of the phosphogypsum between the stack and road construction. The risk assessment should incorporate all handling and processing steps necessary to implement the use. Presumably, pure phosphogypsum would be trucked to a batch plant or other mixing facility, prior to transportation to the construction area. These scenarios should be explicitly considered, including the potential for dust and surface runoff.

Arcadis: Known construction procedures involve PG mixing at the road construction site by placing the PG in the desired location and mixing it into existing or additional soil. Existing calculations consider dust generation at the construction site. These dust intake pathways were found to be orders of magnitude less than external gamma exposure for the construction worker. PG is not batched or mixed prior to use. With respect to loading PG in a truck, the frontend loaders and/or scrapers used to remove PG from a stack to a holding area stockpile at the plant facility for subsequent loading are closed air-conditioned cabs.

Any potential dust exposure to the truck driver or equipment operator is expected to be substantially less in concentration and duration of exposure, compared to the construction worker

For example, as can be seen in the RESRAD output in Appendix C of the Draft Risk Assessment, the annual dose for a road construction worker at the center of the road working on exposed road base, who would experience more direct exposure than a truck driver, inhalation exposure represents 0.5% of the total annual dose. This is presented in the table below.

Road Construction Worker Uranium-238 Dose Exposed to Road Base at Center of Road			
Total Annual Dose (mrem/year)	External Gamma (mrem/year)	Inhalation (mrem/year)	Incidental Ingestion (mrem/year)
28.17	26.11	0.1423	1.918
100.0%	92.7%	0.5%	6.8%

Consequently, the contribution of dust intake for the truck driver or equipment operator is not expected to be relevant to the overall dose and risk calculation.

In addition, consider potential gamma exposures as illustrated by an equipment operator loading the truck using a medium frontend loader. The rate of loading for a 2.25 cubic yards (cy) capacity bucket is 100 cy/hour (Means 2000). Assuming the operator fills ten 20 cy trucks results in an exposure time of two hours per day. In addition, the operator of the front-end loader would be inside a cab located above the PG stack and shielded by the cab. The cab shielding (1 cm of steel) reduces the gamma dose by 50%. This results in the cab operator receiving an annual dose of about 10 % of the construction worker dose (25% exposure duration-2 hours/day and less than 50 % of the gamma dose). The risk is also reduced by at minimum a factor of ten.

11. USEPA: The truck driver scenario only includes direct external exposure from gamma radiation. It should explicitly consider inhalation or ingestion during loading, unloading and truck cleaning.

Arcadis: See comments above. While these additional exposures can be developed, given the discussion in the previous comment, we see no realistic potential for a substantive increase in the calculated risk due to inhalation and ingestion of dust. As described in the response to comment 10, the annual dose for a road construction worker at the center of the road working on exposed road base, who would experience more direct exposure than a truck driver, inhalation exposure represents 0.5% of the total annual dose and ingestion represents 6.8% of the total dose. As a truck driver in the cab of a truck would have less exposure via these routes of exposure than a road construction worker, the relatively small incremental increase in dose has little impact on the resulting risk estimate. Assuming similar percentages for inhalation (0.5%) and incidental ingestion (6.8%) for the truck driver scenario with an annual dose of 18.6 mrem/year, inhalation would be 0.09 mrem/year and ingestion would be 1.27 mrem/year for a total of 20 mrem/year. However, ultimately once converted to risk over a 5-year exposure duration the resulting cancer risk (presented to one significant figure) remains the same (i.e., 20 mrem/year divided by 1,000 mrem/rem, multiplied by the cancer risk coefficient of 5.0×10^{-4} per rem = 5×10^{-5}).

12. USEPA: The utility worker scenario should consider a worker in a trench that parallels the road, rather than crossing it.

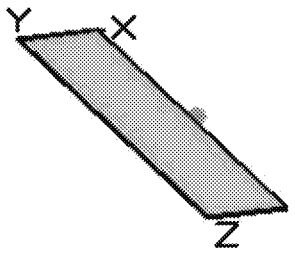
Arcadis: For the Utility Worker Arcadis selected a trench that crosses the road to simply represent an RME scenario, providing a near upper-limit exposure. This scenario provides exposure to an excavated surface on both sides of the worker. The exposure rate as reported in the Risk Assessment is 4.2 µR/hr.

Considering a trench that parallels the road on either side provides only one exposed surface. The result is an exposure rate approximately half (2.15 µR/hr) of the exposure rate arising from the trench considered in the 2019 Risk Assessment. Below are excerpts of a MicroShield output for a trench along the length of the road.

MicroShield Output for Trench Along Length of Road

Source Dimensions	
Length	1.5e+3 cm (49 ft 2.6 in)
Width	1.0e+4 cm (328 ft 1.0 in)
Height	25.0 cm (9.8 in)

Dose Points			
A	X	Y	Z
#1	1.6e+3 cm (51 ft 10.8 in)	25.0 cm (9.8 in)	5.0e+3 cm (164 ft 0.5 in)
#2	1.6e+3 cm (52 ft 10.8 in)	25.0 cm (9.8 in)	5.0e+3 cm (164 ft 0.5 in)
#3	1.6e+3 cm (53 ft 10.8 in)	25.0 cm (9.8 in)	5.0e+3 cm (164 ft 0.5 in)



Shields			
Shield N	Dimension	Material	Density
Source	1.32e+04 ft³	Concrete	2.25
Air Gap		Air	0.00122

Results - Dose Point # 1 - (51.9,8.20e-01,1.64e+02) ft					
Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec	Fluence Rate MeV/cm²/sec	Exposure Rate mR/hr	Exposure Rate mR/hr
		No Buildup	With Buildup	No Buildup	With Buildup
Totals	**1.111e+09**	**5.692e-01**	**1.237e+00**	**9.726e-04**	**2.149e-03**

In the extremely unlikely scenario of a 100 m trench down the center of the road, the resulting exposure rate is estimated by assuming two exposed surfaces results in an exposure rate of 4.3 μR/hr. The incremental length of the trench provides no substantive increase in dose rate due to the extreme angle and distance of the additional exposed surface.

13. USEPA: There may be road user scenarios worth considering, particularly if phosphogypsum may extend beyond the paved areas, e.g., pickup/delivery drivers, workers who mow the shoulders. How would these compare to the currently-modeled scenarios?

Arcadis: As discussed in a previous question, the risk assessment provided an examination of a conceptual road design with risks estimated for scenarios and exposure pathways expected to be the most dominant. The examined exposure scenarios were included in the risk assessment in order to provide the likely maximum scenarios and the scenarios were agreed to by EPA.

The conceptual road design in the risk assessment approximated road design characteristics common in rural, suburban and urban settings and provided plausible exposure scenarios for various types of roads. While larger highway designs could be built, these require larger right-of-way widths of approximately 150 to 300 feet.[18] This leads to larger set-backs for near-by residential housing, resulting in lower dose and risk. Interstate highways typically have restricted access to cyclists and pedestrians, eliminating these

[18] The Federal Highway Administation, Highway History, The Size of the Job, available at [HYPERLINK "https://nam02.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.fhwa.dot.gov%2Finfrastructure%2F50size.cfm&data=02%7C01%7Cjohn.stolys%40arcadis.com%7Cbc120b78c8454cab9dbe08d7d46f8afe%7C7f90057d3ea046feb07ce0568627081b%7C1%7C0%7C637211449697708910&sdata=ZhCvQ

exposure scenarios for large highways. Suburban and urban roads represented a plausible scenario which maximizes exposures for the dominant external gamma pathway.

With respect to pickup/delivery drivers and workers who mow the shoulders the dose assessments for road users provided in the 2019 risk assessment would be bounding and estimate higher doses than doses for other types of road users.

For example, a truck driver may drive 50% of the workday but would likely be on PG road only 25% of the driving hours due to the use of the extensive network of existing roads. Drivers in delivery trucks would also gain the benefit of shielding from the vehicle structure, which is typically a factor of approximately 0.6 (BID 1992). Overall, a scenario with a delivery driver is estimated to result in a dose that is approximately 30% of that estimated for the road user in the 2019 risk assessment.

A worker mowing the grass beside the road may be working for close to a full day but again would likely be beside a PG road only 25% of the driving hours due to the work on the extensive network of existing roads. This worker would also gain the benefit of shielding from the vehicle structure, which is typically a factor of approximately 0.6 (BID 1992). Considering the worker is located beside the road, the exposure to PG is reduced by approximately 50%, as shown in the 1992 risk assessment. Overall, a scenario with a worker mowing grass beside the road is estimated to result in a dose that is approximately 30% of that estimated for the road user in the 2019 risk assessment.

Parameters:

14. USEPA: The worker exposure duration of 5 years is based on both 25% of a 20-year career and of 70% of the project completion time for a major road project (p. 2-9). If the use of phosphogypsum as road base becomes regular practice, would workers not be expected to work on subsequent projects that could also involve phosphogypsum?

Arcadis: The road construction project examples provided in the discussion of this parameter were some of the largest (longest) projects identified. The parameter estimation uses worker statistics and the likelihood of other road construction methods to continue, to estimate a reasonable exposure duration over a construction worker's career.

The Bureau of Labor Statistics employee tenure in 2018 shows that the median years of tenure with current employer for construction industry between 2008-2018 ranges from 3.5 years in January 2008 to 4.3 years in January 2012 (See Table 5 below).

Table 5. Median years of tenure with current employer for employed wage and salary workers by industry, selected years, 2008-2018

Industry	January 2008	January 2010	January 2012	January 2014	January 2016	January 2018
Total, 16 years and over	4.1	4.4	4.6	4.6	4.2	4.2
Private sector	3.8	4.0	4.2	4.1	3.7	3.8
Agriculture and related industries	4.3	4.8	4.1	3.8	4.5	4.6
Nonagricultural industries	3.8	4.0	4.2	4.1	3.7	3.8
Mining, quarrying, and oil and gas extraction	4.1	4.8	3.5	4.0	4.8	5.1
Construction	3.5	4.2	4.3	3.9	4.0	4.1

Burmaster (2000)[19] analyzed employee tenure data from The Bureau of Labor data. The report provides statistical analysis of those data for a wide variety of occupations. For construction in general, the data for men (women not available) show a mean and 95th percentile of 3.23 yr and 12.48 yr. For construction laborer's specifically, the data for men/women show a mean and 95th percentile of 1.74 yr / 1.81 yr and 5.93 yr / 7.08 yr, respectively.

Burmaster (2000) also provides the distributions (in terms of empirical percentiles) for projected duration in years for each occupation type. The table below shows the worker tenure percentile projections for these selected industrial subsectors.

Distribution of Male Worker Tenure by Industry Type

Industry Sector		Percentiles											
	Mean	10	20	30	40	50	60	70	80	90	95	97.5	99
Construction	3.23	0.21	0.45	0.74	1.10	1.54	2.13	2.98	4.39	7.70	12.48	18.24	26.23
Construction Labor	1.74	0.10	0.22	0.36	0.53	0.74	1.01	1.40	2.03	3.45	5.93	11.53	21.26

To be consistent with methodologies to determine RME exposures and risk Arcadis considered that not all construction work will be on PG roads due to possible alternate construction methods and maintenance work for the vast network of existing roads.

The value used in the Risk Assessment represents a portion of industry tenure spent constructing roads: 80% of 25-year worker tenure recommended by USEPA (2014) constructing roads = 20 years; 25% of road construction time spent using PG = 5 years. Based on the employment statistics provide above the actual exposure is likely to be much less than 5 years.

15. USEPA: The TFI Risk Assessment for the Truck Driver scenario uses a density of 1.12 gm/cm3 for phosphogypsum in the truck. U.S. Department of Transportation, Federal Highway Administration, Research and Development Turner-Fairbank Highway Research Center, User Guidelines for Waste and By-Product Material in Pavement Construction, FHWA-RD-97-148 gives a specific gravity range from 2.3 – 2.6 gm/cm3 (p. 19-6), and in a second location states, "specific gravity of solids ranges from 2.30 to 2.50, with an average in the 2.35 to 2.40 range." (p. 19-14). TFI assumes that loose PG in the truck will be about half the density of that identified in the FHWA document. PG that is excavated and loosely placed in a truck will certainly have a higher porosity, but what is the basis for assuming this specific value?

Arcadis: The specific gravity values of 2.3 to 2.6 (unitless) are common in literature about PG. For example, Chang and Mantell 1990[20], reported the average specific gravity values of seven Florida

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[19] Burmaster, David E., 2000, *Distributions of Total Job Tenure for Men and Women in Selected Industries and Occupations in the United States, February 1996*. Risk Analysis, Vol. 20, No. 2, 2000.
[20] Chang, Wen F., and Mantell, Murray I., 1990. Engineering Properties and Construction Applications of Phosphogypsum, University of Miami, Phosphate Research Institute, ISBN No. 87024-328-4.

sources of PG varied between 2.33 and 2.43. The specific gravity values of this magnitude however related to particle specific gravity and ignores the porosity / void space in the bulk material. The same reference reports the maximum dry bulk density of PG following compaction to range between 90.3 to 102.7 lb/ft^3. This compacted bulk density converts to 1.4 to 1.6 g/cm^3. For material excavated and loaded into a truck a swell factor of 20% - 30% is not uncommon for materials such as soil, sand or gravel. For the Risk Assessment the density of the PG in the truck can be supported using a bulk density of 1.4 g/cm^3 with a swell factor of 25% (1.4/1.25) resulting in PG density during transport of approximately 1.12 g/cm^3.

As previously indicated, density is an important factor in assessing potential doses arising from road building. The in-place post compaction density of PG in road base will be specified along with other physical characteristics by the appropriate local, state or federal highway authority. The densities used in the current (2019) risk assessment are considered appropriate for the purpose of risk assessment.

16. USEPA: Assumed inhalation rates may need further justification. As stated in the TFI Appendix 2 (p. 2-11): "The RESRAD default inhalation rate of 8,400 cubic meters per year (m3/yr) was used for the nearby resident receptor. A higher inhalation rate of 11,400 m3/yr was assumed for road construction workers and utility workers. This value was the RESRAD version 6 default for industrial workers and assumes an hourly rate of 1.3 m3/hr." When 11,400 m3/yr is multiplied by the fraction of time spent outdoors (on site) the result is the Road Construction Worker annual inhalation rate of 2,622 m3/yr. This value is about 9% larger than the worker inhalation rate used by the International Commission on Radiation Protection (Guide for the Practical Application of the ICRP Human Respiratory Tract Model, 2002). However, compared to the EPA Exposures Factors Handbook (EPA 2011) Tables 6-1 and 6-28, the inhalation rates for moderate and heavy activities, the RESRAD rate of 1.3 m3/hr is lower than the low end of the range provided for EFH worker inhalation rate. The low end of the range is 1.6 m3/hr and the high end is 4.8 m3/hr, several times higher than the RESRAD rate.

Arcadis: RESRAD exposure parameters for workers were applied where available. Considering the exposure duration of a full day, it is expected that a moderate inhalation rate would be more realistic of the overall inhalation rate as heavy activities would not be continuous throughout the day. The values in Table 6-28 of EPA Exposure Factors Handbook (EPA 2011) ranging from 1.6 m^3/hr for the low end of the moderate activity level, which is for adult females, to 4.8 m^3/hour for the high end of the heavy activity level, which is for adult males, is based on information included in a dated guidance document (i.e., EPA 1985).

More recent studies are referenced in the Exposure Factors Handbook (EPA 2011), several of which were specifically conducted on workers or more specifically construction workers. One study of "high risk" populations exposed to ozone in the Los Angeles area found a mean inhalation rate of 0.78 m^3/hour for healthy adults and a mean of 1.5 m^3/hour for construction workers during a 10-hour work shift (Linn et al. 1992). Linn et al. (1993) studied inhalation rates of construction workers (i.e., laborers, iron workers, and carpenters) during work and break times based on a relationship to heart rate and determined a mean inhalation rate of 1.68 m^3/hour with a standard deviation of ± 0.72. However, estimates of extremes (e.g., 99th percentile) were outside the calibration range of the model and would not be appropriate for an RME. Lastly Allan et al. (2009) determined mean inhalation rates of 1.4 m^3/hour for male construction workers and 1.25 m^3/hour for female construction workers based on probability density distributions generated using Monte Carlo simulation. Therefore, the inhalation rates used which are based on RESRAD defaults are appropriate mean estimates.

While upper percentile estimates may represent a relative extreme, those assumptions are not appropriate for a reasonable maximum exposure scenario. Regardless, using an inhalation rate up to 3 times higher resulting in inhalation doses 3 times higher would still add relatively little to the overall dose and risk as the inhalation route of exposure results in a dose that is orders of magnitude less than external radiation and an order of magnitude or more less than ingestion exposure.

17. USEPA: It is difficult to evaluate the appropriateness of the worker exposure parameters TFI used in Appendix 2, in part due to a lack of detail in discussion of road base and pavement construction process, procedures, and equipment. Page 3-2 states "it was assumed the road construction worker moves around the surface of the road and the direct dose was calculated as the average of the dose at the road center and at the edge of the road." Would different workers have different roles, such as walking directly behind machinery versus walking on the road shoulder? What would happen to the doses if this ratio was changed, such as 75% middle of the road/ 25% edge?

Arcadis: The assumption of the construction worker exposure at both the center of the road and the edge of the road approximates the expected movement of a worker throughout a full workday. Shifting this parameter to the extreme of working 100% of the time in the center of the road would provide a minor increase in the exposure and risk.

As shown in the calculations in a previous question above, assuming the worker spends 100% of the time in the center of the road provides an annual exposure of 28 mrem/yr. This is a 27% increase from the 22 mrem/yr exposure reported in the risk assessment, based on 50% in the middle of the road and 50% along the edge of the road, but makes no change to conclusion that the risk is significantly below 3:10,000. But it is unrealistic to assume a work stands in one spot all day. If a worker did so, he or she would have a very low inhalation rate.

ECONOMIC ANALYSIS OF PHOSPHOGYPSUM REUSE

The Fertilizer Institute

Submitted by:

Policy Navigation Group

December 2019

EXECUTIVE **SUMMARY**

Policy Navigation Group (PNG) conducted this analysis on behalf of The Fertilizer Institute (TFI) to esti mate the potential regulatory cost savings of changes that would expand the use of phosphogypsum (PG) to include road construction. This application is in use tn Europe and elsewhere, but currently is precluded in the U.S. due to U.S. Environmental Protection Agency (EPA) regulatory restrictions. This section outlines the main steps we undertook to perform the analysis and summarizes the economic benefits of using PG for road construction.

Outline of Steps in Analysis

In the analysis that follows, we take these steps to estimate the potentf al cost savings of using PG for road construction:

> Identify the costs to manage PG currently in stacks located at numerous sites. These include the costs of land for the stacks, the costs to transport PG to the stacks, the costs of managing water at and preserving the physical stability of the stacks, and the costs to close the stacks.
>
> Assess scenarios for PG reuse in road construction in the near future. We assume that PG reuse will start modestly and growover time. Given market uncertainty over the potential demand for PG, we estimate the savings for a lower-bound and an upper-bound scenario; any savings are expected to be within this range. Due to transportation costs and the availa bility of substitutes, we assume that the PG reuse market faces natural limits and largely is confined to locations relatively close to current plants and stac ks.
>
> Estimate the cost savings from PG reuse. Companies can incur savings in PG manage me nt costs if they send PG t o be reused (stack manage ment savings from the regulat ory reform). Since the stack management savings from the regulatory reform frees up the labor, capital, and physical land needed for PG stack management, in competit ive markets some of these savings are passed through to the companies• customers and purchasers of PG for reuse. Ultimately the savings pass through to the state and local highway departments, companies' shareholders, companies• workers, farmers and other purchasers of fertilfzer, and other households and firms.[1] For this reason, these cost savtngs are atso the social benefits of the reform. They are also the deregulatory savings from an EPA action to allow reuse for road const ruct ion.

Figure ES-1 summarizes the key inputs used in the analysis and shows the data transformati on and resulting outputs.

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[1] In this analysis, we only consider the direct economic impact of the reform. There will be indirect and induced economic impact of the reform as fertilizer customers have lower input costs and can gain market share from imports and as workers spend their greater compensation on consumer goods and services. These gains then induce additional economic impact such as higher spending by vendors to the fertilizer ,e.urchaser and the workers.

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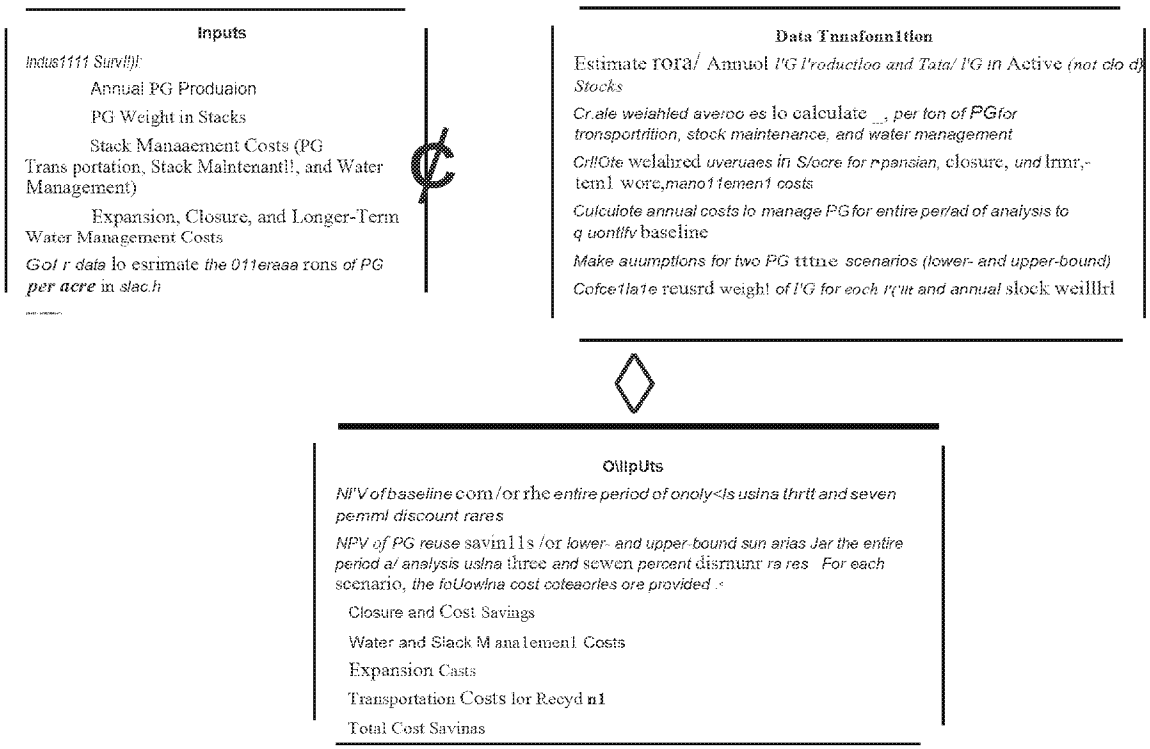
Figure ES-1: Diagram Summarizing Analytical Approach for Proj ect [2]



Summary of the Regulatory Savings

The analysis produced by taking the steps above provides a clear picture of the cost savings of using PG for road construction. Table ES-1 presents the baseline costs to manage PG from 2020-2042, which range from $1.3 billion to $0.88 billion using three and seven percent annual discount rates. Table ES-2 summarizes the cost savings from PG reuse for the two reuse scenarios; it shows that the total net present value (NPV) savings range from $37 million to $52 million for the lower-bound scenario and from $110 million to $160 million for the upper-bound scenario, using discount rates of seven and three percent, respectively.[3] We use three and seven percent discount rates to calculate the results from this analysis, as directed by U.S. Office of Management and Budget Circular A-4.

[2] We use three and seven percent discount rates to calculate the results from this analysis, as directed by the U.S. Office of Management and Budget's Circular A-4.

[3] The results presented in this analysis are rounded to two significant figures. Due to rounding, total values in the tables mat notsum.

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Table ES-1: Net Present Value (NPV) of Baseline Costs to Manage PG

CATEGORY	NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)
Baseline Costs	1, 300	**880**

Table ES-2: Net Present Val ue (NPV) of Cost Savings from PG Reu se

COST CATEGORY [4]	LOWER-BOUND SCENARI O	LOWER-BOUND SCENARIO	UPPER-BOUND SCENARIO	UPPERBOUND SCENARIO
	NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	**NPV USING A 7%** DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)
Cl osure Cost Savings	11	11	33	32
Water and Stack **Management Costs**	22	13	65	37
Expansion Cost s	**19**	13	57	**38**
Total Cost Savings	**52**	37	**160**	110

In summary, expanding the use of PG in road construction is expected to result in savings not only to PG produ cers, but also to numerous users of PG and workers, sha r eho l d ers, and customers of fertilizer firms.[5]

[4] Transportation sa vings are omitt ed from the results shown in this table as they amount to zero dollars. Transportat ion cost from the stack to the const ruction site is not incl uded because it is assumed t hat the cu stomer would pay for this t ransporta tion as part of the road construction cost .

[5] Savings to users of PG, workers, shar eholders, and customers of fert ilizer firms are not evaluated in this economic ana lr sis.

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INTRODUCTION

Policy Navigation Group (PNG) conducted this analysis on behalf of The Fertilizer Institute (TFI) to estimate the potential regulatory cost savings of using phosphogypsum (PG) for road construction, an application currently in use in Europe and elsewhere. This section provides a summary of the industry, followed by a description of PG, its production in the U.S., and U.S. Environmental Protection Agency (EPA) PG requirements. It then touches upon PG reuse options and scenarios before concluding with a description of how the remainder of the report is organized.

Summary of Industry

Phosphate rock is predominantly used to produce phosphoric acid, which is primarily used to manufacture fertilizer. The U.S. was previously the largest producer of phosphate rock and leading exporter of phosphate fertilizer, until China increased its production in 2011 and surpassed the U.S. as lead world exporter in 2014.[6] Currently, the U.S. is the second-largest consumer of phosphate rock (consuming 29 million metric tons (MT)) and the second-largest producer of phosphoric acid (producing 14 million MT).[7] Domestically, phosphate rock ore is mined primarily by five firms in four states - with 80 percent of the mining occurring in Florida and North Carolina - to produce approximately 27.1 million tons of marketable product.[8] After being mined in open-pit mines, phosphate rocks are treated, washed, and dried in rotary kilns.[9] The ore is then finely ground and converted into a soluble form through either a wet or dry process. In the U.S., facilities exclusively use a wet process that digests the phosphate rock in a reaction vessel with sulfuric acid, producing both phosphoric acid and a largely calcium sulfate byproduct known as PG.

Total worldwide production of PG is estimated between 100-280 mega tons per year.[10] About 85 percent of world PG production is discarded or stored. The remaining 15 percent of worldwide production is reused as soil amendment, agricultural fertilizer, and set controller for cement and building materials worldwide.

Around the world, PG is used in a range of applications, including:[11]

- In fertilizer for agricultural soils;
- In backfill and road-base material for roadway and parking lot construction;
- As an additive to concrete and concrete blocks;

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[6] Jasinski, "Phosphate Rock."

[7] European Phosphate Fertilizer Alliance, "Data and Statistics: Phosphoric Acid."

[8] Jasinski, "Phosphate Rock."

[9] U.S. Environmental Protection Agency, "Potential Uses of Phosphogypsum and Associated Risks: Background Information Document for 40 CFR 61, Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks."

[10] Sahu et al., "Natural Radioactivity Assessment of a Phosphate Fertilizer Plant Area."

[11] U.S. Environmental Protection Agency, "Potential Uses of Phosphogypsum and Associated Risks: Background Information Document for 40 CFR 61, Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks."

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- In wallboards;
- In mine reclamation; and
- In the recovery of sulfur.

Prior to the 1992 EPA restrictions on its widespread reuse, PG was critical to the peanut industry as a soil amendment valued for its fertilizer properties across Georgia, North Carolina, Virginia, and Alabama, and on farms across the southeast that grow tobacco, corn, small grain, and sugar cane.[12] As a large peanut producer, Georgia was the largest PG consumer. States such as California also used PG for soils growing citrus, almonds, vegetables, and tomatoes. In these and other locations, PG was widely used, since it had been shown to be a beneficial source of sulfur in improving crop yields.

Description of Phosphogypsum

PG byproduct is filtered from the phosphoric acid and transferred as a water slurry to be stored in open-air areas called PG stacks. The slurry is pumped atop the stack, where an engineered "gypsum stack and pond" is formed. Water impounded from PG stacks is reused in the overall wetting process. Closing PG stacks involves complex engineering, including placing high-density polyethylene liners as caps to prevent rainwater from infiltrating and reduce stack water from percolating out from the bottom of the stacksn.

Reuse Options and Scenarios

Other countries, most notably Japan and some nations in Europe, have and currently reuse some PG for specified uses that have included road base material, cement, wallboard, and other building materials. [14]

Road Base

Prior to EPA restrictions on its use in 1992, PG was mixed with ash, sand, gravel, or cement, and was used as a base for roads, parking lots, and storage areas to help control setting times, counteract shrinkages, strengthen cement products, and create resistance to sulfate etching.[15] Numerous publications are available detailing these uses. The following are some examples of how PG was used in Texas, Florida, and North Carolina: [16]

- In Pasadena, Texas, PG was mixed with fly ash and cement for road base at five sections of city streets in La Porte, Texas.
- In Polk County, Florida, PG was mixed with granular sand to construct 2.4 kilometers of road base, surfaced with asphalt.

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[12] U.S. Environmental Protection Agency.

[13] BCI Engineers & Scientists, Inc., "Phosphogypsum Stack Closure: Evaluation of Phosphogypsum as an Alternate Final Cover."

[14] U.S. Environmental Protection Agency, "Potential Uses of Phosphogypsum and Associated Risks: Background Information Document for 40 CFR 61, Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks."

[15] U.S. Environmental Protection Agency.

[16] U.S. Environmental Protection Agency.

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- In Columbia County, Florida, two miles of road base was constructed with 100 percent dehydrated PG and varying mix ratios of PG and sand. The road base was also surfaced with asp ha lt.
- In North Carolina, PG was comme rcially used as a fill and sub-base for roads in swampy areas.
- In Ba rtow, Florida, the Florida Instit ute of Phosphate Research used a mixt ure of PG and concrete to pave two thousand yards of driveway and parking areas.

Ce me nt and Concrete Aggregate

PG also has been used to manufacture building materials, includi ng concrete and cement aggregates, particularly outside the U. S.[17] Additionally, it can be used more extensively in building ma te rials, including ce ment , wallboard, ferrocement panels, plasterboard panels, partition blocks, plaster, tfles, artificial stone, and glass ceramics. [18]

Several studfes have demonstrated that PG can help prolong concrete setting times.[19] The increased setting time supports long-term concrete strength. Incremental initial and final setting times increase with increasing PG content. Using PG as a retarder agent is particularly beneficial in civil engineering work involving casting in hot weather, casting retaining deep walls, and casting mass concrete and repair ele me nts , for example.[20]

I ncluding PG in cement also has the benefit of reducing density, increa si ng chemical resistance, increasing free resistance, and increas ing fire resistance. [21] As such, PG has the potential to be used as a partial substit ute for materials aggregate in concrete.

Organization of the Report

The rest of the report discusses current PG manage me nt costs and incurred savings from PG reuse, showing how we developed scena rios for PG reuse and estimated the cost savings for these scenarios. Since the regulatory change frees up the labor, capital , and physical land needed for PG stack manageme nt , these savings are also the social benefits of the regulatory reform.

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[17] U.S. Environmental Protecti on Agency.

[18] Rashad, "Phosphogypsum as a Construction Materi al. "

[19] Rashad; Shen et al. , " Calci um Sul p h oaluminate Cements Made with Phosphogypsum: Production Issues and Materi al Prope rt ies"; Singh, "Treating Waste Phosphogypsum for Cement and Plaster Manufacture"; Altun and Sert, "Utilization of Weathered Phosphogypsum as a Set Retarder in Portland Cement."

[20] Rashad, "Phosphogypsum as a Construction Mat erial. "

[21] Rashad.

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CURRENT PG MANAGEMENT COSTS AND COST SAVINGS FROM PG REUSE

Introduction and Methodology Overview

This section provides an overview of current PG production and PG stored in stacks; details and quantifies the current costs of PG management; describes and quantifies the potential short- and long-term cost savings if a percentage of currently produced PG is reused for road construction; provides baseline and PG reuse scenarios to illustrate several key points; and presents the variables, assumptions, and methodology used in all the above.

A survey was conducted with members of TFI in July 2019. The survey included questions on current PG production; weight of PG stored in active stacks; and costs to transport, manage, expand, and close stacks. The survey was conducted, compiled and summarized by an independent party who removed identifying information before data was provided to PNG for analysis. The survey questions are provided in Appendix 1.

Using the survey information, we estimate averages for current production, average weight of PG stored in active stacks, and costs. With these estimates, we calculate the current costs of managing PG - the baseline costs. Then, we create two scenarios (lower- and upper-bound) to estimate the cost savings if a percentage of the PG produced is beneficially reused.

The timeline of the analysis is from 2020 to 2042. All future values are discounted using a three and seven percent discount rate and presented in 2019 dollars. [22] The values in the tables are rounded to two significant digits. Therefore, the totals shown in some tables may not sum exactly. We only consider active PG stacks for this analysis, as according to information received from the industry, it is unlikely that PG from closed stacks would enter the reuse market.

PG Production and Annual Growth Rate

Survey participants provided annual PG production data (in tons per year) for 2016, 2017, and 2018 for nine active stacks. Data was provided by the largest PG producers in the U.S., but it does not include all active stacks and PG producers in the country. To account for variability across stack data (both, on annual basis and by stack), we calculate weighted averages. To calculate the weighted annual production rate, we estimate the average growth (in tons) for each stack from 2016 to 2017 and from 2017 to 2018. Then, we estimate the corresponding weighted average growth rate for each period (from 2016 to 2017 and 2017 to 2018). We derive industry representative weighted averages by weighing each stack's size by its proportion of the sum of the size for all the stacks in the survey.

To estimate the annual production of PG available for reuse, we calculate the weighted average across all the active stacks. For this estimate, we quantify the multi-year average per active stack (from 2016 to 2018) and then the weight of the multi-year average per stack in relation to all the active stacks. This gives a weighted average annual production of PG of 5.1

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[22] U.S. Department of Labor. Bureau of Lal:>or Statistics, "CPI Inflation Calculator."

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million tons. We multiply this value by nine stacks to obtain a weighted annual total U.S. production of 46 million tons of PG.

For this report, we assume that PG production in the U. S. will not experience growth in the timeline of the analysis - that it will remain at the same level as in the baseline. We make this assumpt ion because information received from the industry for this analysis forecasts no growth. Furthermore, the survey data spans only a three-year period and varies by company and year, rendering it difficult to determine any long-term trend in terms of growth. We note that this assumption is in line with market reports from Europe, which show near-zero growth for PG production between 2012 and 2017.[23]

Table 1 summarizes the PG productio n data used for the analysis.

Table 1: PG Production

ITEM	AMOUNT
Weighted Average of Production , Per Year, Per Stack	5,100,000 tons
Total Annual Production of PG	46,000,000 tons

PG Stored in Stacks

For the nine active stacks discu ssed in the previous subse ction, we received the approximate amount of PG stored in each. For eight of the nine stacks, the weight was provided in tons. For one of the stacks, we were provided the volume in cub ic yards, which we converted into tons using a density factor of 1.9 tons per cubic yard.[24]

The surveyed companies also provided informat ion for inactive stacks, as PG from inactiv e stacks may be used.

Using the survey information, we add the tota l weight in both active and inactive stacks. Additionally, we calculate the weighted average tons for both types of stacks by creating we ights per stack (that is, how much each stack represents of t he total in the corresponding catego ry). These weights are further used to est f mate the average costs per ton (see subsection below).

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[21] Lay r and Hartlieb, "Market Analysis for Urban Mintng of Phosphogypsum."

[24] City of Moorpark, "Construction Demolition Conversion Table." This value comes from a conversion factor for wpsum used in drywall.

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Figure 1: Projected New PG Production and PG in Stack s[25]

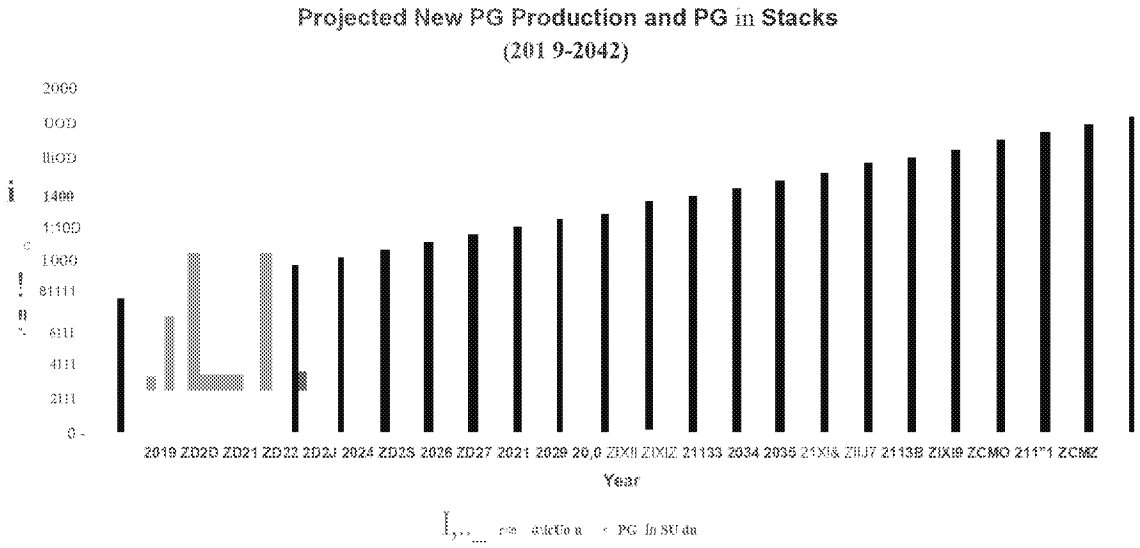

Table 2 summarizes the PG stored in stacks and Figure 1 shows both the PG in stacks and the projected new production of PG. While the period of analysis is 2020-2042, Figure 1 includes data for 2019, as the PG in stack value for 2020 must include the weight for 2019.

Table 2: PG in Stacks

ITEM	ACTIVE STACKS	INACTIVE STACKS	TOTAL
Total PG Stored (milllon **tons)**	517	217	734
Weighted Average Per Stack (mlilllon **tons)**	69	65	NIA

Costs to Manage PG

In response to the survey, companies provided annual costs per stack for the following categories[26]:

- Transportation costs - costs to transport PG from the plant to the stacks
- Stack maintenance costs - labor, monitoring, inspectton, and reporting costs
- Water management costs - costs for water balancing and water treatment

[25] Figure 1 reflects the current baseline and does not show the PG reuse scenarios discussed later in the analysis.

[26] The cost information was provided by stack and was not tied to PG production levels.

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We then use the weights calculated for PG production and PG stored in stacks (see previous subsections) and apply those to the survey data's cost per stack. For the transportation costs, we use the weights for PG production, as tr ansportation costs are i ncurred in transporting PG from the plant to the stacks; once the PG i s in place at the st ack, no additional transport ati on costs are assumed to be incurred. For stack maintenance and water management costs, we use the weights corresponding to PG stored in stacks and apply them to the whole amount of PG stored in a stack. Then, we calculate the weighted average cost per category. To do this, we multiply the corresponding weight by the cost per year per st ack, add those product s, and divide the resulting sum by the sum of the weights used. Finall y, we obtain the average cost per ton by dividing the weighted average by the number of tons per cost category.

The volume of water generated and treated (the water management volume) can be affected by factors such as weather condi tions, the manufacturi ng process, and the age of the PG. The major climate consideration would be variability in precipitation among different geographic regions. While water management volumes would decrease over time due to reduction in size and number of PG st acks, it would not completely disappear. As with alt new sustainability strategies, innovation and synergies may lead to additional water management reductions as yet to be determi ned .

Thus, in practice, the stack water generation and treatment volumes can vary signi fi cantly by the location and by the age of the stack. Whi te we asked r espondents for typical, current values for wate r management costs, we are unaware if respondents provided data that represents average climate conditions and PG aging.

Table 3 provides the weight of PG in active stacks, the weighted average costs and the cost per ton for the three cost categories.

Table 3: Weight of PG in Active Stacks and Costs

ITEM	TRANSPORTATION COSTS	STACK MAINTENANCE COSTS	WATER MANAGEMENT COSTS
Weighted Average ($ millions)	7.2	6.8	7.4
Total Tons of PG in Category (mUtion **tons)**	8.3	570	380
Average Cost Per Ton ($) [27]	0.87	0.012	0.02

[27] Average cost per ton is obtained by dividing the weighted average by total tons of PG. For example, for transportatfon costs 7.2/8.3 =$0.87. Note that values in the tab le are rounded to two significa nt figures as noted ea rlier in the analysis. As a result , total values in table may not sum exactl y.

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Other Stack-Related Costs

Survey participants indicated that, in addition to transportation, water management, and stack maintenance costs, there are other long-term costs associated with PG stacks - stack closure costs, water inventory costs, and stack expansion costs. These costs are expected to be incurred in the next five years (between 2020 and 2024).

To avoid providing identifiable information, the surveyed companies provided costs for those long-term categories in dollars per acre of PG stack. In some instances, they provided a lower- and upper-bound estimate for the category. Also, some companies reported zero costs for the category or reported them as part of another category. For this analysis, we create upper- and lower-bound estimates per category, then calculate the middle-point value. Table 4 outlines these costs.

Table 4: Long-Term Costs of PG Management

ITEM	STACK CLOSURE COSTS	WATER INVENTORY COSTS	STACK EXPANSION COSTS	TOTAL	UNIT
Average-Lower Bound	**91,000**		**220,000**	330,000	$/acre
		23,000			
Average-Upper Bound	100,000		240,000	360,000	$/acre
Total **Average**	96,000	23,000	230,000	350,000	$/acre

Cost Summary

Table 5 summarizes the cost savings due to PG reuse. The most significant savings occur from deferring stack closure and expansion, which together represent almost $350,000 per acre of PG. Since one stack can contain more than 70 million tons of PG, the cost savings of reusing PG are significant.

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Table 5: Sh ort - and Long-Term Costs of PG Management

ITEM	COST	COST TYPE	UNIT
Transportation Costs	0.87	Short -term	$/ton
Stack Maintenance Costs	0.01	Sh ort -term	$/ to n
Water Management Costs	0.02	Short -t tt m	$/ton
Stack Closure Costs (Includes water Inventory costs)	120,000	Long- t erm	**$/ acre**
Stack Expansion Costs	230,000	Long-term	**$/acre**

Cost Savings from PG Reuse Scenarios

Baseline Scenario

In this scenari o, we quanti fy the current costs of managing PG at phosphoric acid plants. As ou tlt n ed in Table 1, the weighted annual PG production is approximately 46 million tons. Figure 1 outlines the total amount of PG expected to be produced per year from 2020 to 2042. It also presents the amount of PG expected to be stored in stacks during that same period. Given the current regulatory restrictions on using PG, this scenario assumes that all new PG produced is put into stacks.

To estimate the costs for the baseline scenario , we first mul tiply the weighted annual production of PG by the transportation costs per ton ($0.87). We then multiply the weight of PG stacked by the sum of stack maintenance and water management costs per ton of PG ($0.03). Finally, we add the transportati on, stack maintenance, and water management costs for the entire period and calculate the net present value (NPV) using discount rates of three and seven percent.

PG Reuse Scenarios

Lower-Bound Scenario

In this scenario, we assume that a percentage of PG produced annually is reused. When PG is reused rather than put into st acks, PG producers incur savings in water management costs, stack maintenance costs, and long-term savings for the amount of PG reused; the only costs they incur are those associated with transport of PG from the facility to the construction site. The NPV of these cost savings minus the transportation costs to the construction site (at discount rat es of three and seven percent) are the results for this scenario.

This scenario assumes that five percent of current PG production is reused in each year in 2020 and 2021, 7.5 percent is reused each year in 2022 and 2023, and 10 percent is reused

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in 2024 (see Table 9). Between 2025-2042, the assumed reuse percentage remains at 10 percent. We arrive at this representative reuse scenario by assuming that the PG reuse market will start slowly due to the availability of competing products that already have market share and may be sold through longer-term contracts. Additionally, since PG has been off the market for almost 20 years, this assumption accounts for the idea that it may take PG sellers some time to convince potential customers of PG's beneficial qualities. With these assumptions in place, we calculate water management, and stack maintenance savings by multiplying the sum of the annual weight of PG reused (in tons) plus the weight of PG reused in previous years by $0.03 (see Table 6).[28]

Upper-Bound Scenario

In this scenario, we assume that PG suppliers will offer favorable pricing relative to competing products, effectively promoting greater PG reuse that grows robustly over time. Specifically, we assume that 10 percent of current PG production is reused in 2020, 15 percent is reused in 2021, 20 percent is reused in 2022, 25 percent is reused in 2023, and 30 percent is reused from 2024 (see Table 6). As in the lower-bound scenario, we arrive at this representative reuse scenario by assuming that the PG reuse market will start slowly due to the availability of competing products that already have market share and may be sold through longer-term contracts, and that it may take PG sellers some time to convince potential customers of PG's beneficial qualities. With these assumptions in place, we calculate water management, and stack maintenance savings by multiplying the sum of the annual weight of PG reused (in tons) plus the weight of PG reused in previous years by $0.03 (see Table 6).

[28] Water management and stack maintenance savings are recurrent annual costs. Therefore, they are calculated over the sum of PG reused in a given year plus PG reused in the previous years. For example, for the upper-bound scenario in 2022, water management and stack maintenance savings are calculated over 20.7 tons (sum of amount reused from 2020-2022).

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Table 6: PG Reused

YEAR	LOWER-BOUND SCENARIO PERCENTAGE REUSED(%)	LOWER-BOUND SCENARIO AMOUNT REUSED (MILLION TONS PER YEAR)	UPPER-BOUND SCENARIO PERCENTAGE REUSED(%)	UPPER-BOUND SCENARIO AMOUNT REUSED (MILLION TONS PER YEAR)
2020	5	2.3	10	4.6
2021	5	2.3	15	6.9
2022	7.5	3.5	20	9.2
2023	7.5	3.5	25	12
2024	10	4.6	30	14
2025	10	4.6	30	14
2026	10	4.6	30	14
2027	10	4.6	30	14
2028	10	4.6	30	14
2029	10	4.6	30	14
2030	10	4.6	30	14
2031	10	4.6	30	14
2032	10	4.6	30	14
2033	10	4.6	30	14
2034	10	4.6	30	14
2035	10	4.6	30	14
2036	10	4.6	30	14
2037	10	4.6	30	14
2038	10	4.6	30	14
2039	10	4.6	30	14
2040	10	4.6	30	14
2041	10	4.6	30	14
2042	10	4.6	30	14

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Comparison of Reuse Scenario versus Current Demand for Road Construction

We compare this reuse scenario to the size of local markets as one measure of the reasonableness of the scenario. To validate that our assumptions on PG reuse are feasible given the overall size of the road aggregate market, we contacted the Florida Department of Transportation. We selected Florida as a representative construction market since a majority of the nation's PG is generated in Florida.

Due to the high cost of transporting PG to be used in road construction, we consider that the potential demand for PG is limited to within one day's hauling of the production location, or approximately 200 miles. Both the lower and upper bound scenarios of PG reuse are well within Ronda's projected future demand for aggregate for road construction.

Stack Closure Costs

We assume that by reusing a percentage of current production, PG producers will be able to defer stack closure costs. Thus, less PG would need to be stored in stacks, and current stack capacity would last longer. However, it is difficult to predict the number of stacks that may be closed - or expanded - in the period of analysis (and thus estimate the potential cost savings from those deferred stack closures). We believe this to be the case based on insights provided by survey respondents, which suggest that stack closure and stack expansion decisions require long-term strategic planning and are subject to company-specific PG production forecasts and stack capacity.

Recognizing the limitations of generalizing from company-specific conditions to a industry-representative average, in this analysis, we start by assuming that stack closure costs are deferred until 2039 for both the lower- and upper-bound scenarios. The assumption that a stack is closed in 2039 is consistent with historic stack closure reports, as stacks are generally closed after reaching a certain acreage. The purpose of this estimate Is to show the potential savings that could arise from deferring stack closure due to PG reuse. For these estimates, the closure cost per acre of PG corresponds to the sum of the water inventory management and stack closure costs ($120,000). Closure occurs in 2039, but the period of analysis covers years until 2042 to allow for the completion of active stack closure activities.

The weight of PG in the survey is provided in tons, while the long-term costs are provided in dollars per acre. Therefore, we next need to estimate how much PG is generally found in one acre. For this estimate, we use a dataset with stack data for Florida. [29] This dataset has information on stack area and length. We assume that all stacks in the Rorida dataset are 100 meters in height, have a rectangular base, and have a side slope of 1:3. To estimate the stack width, we divide area by length. Then, we calculate the volume per stack and multiply that volume by an assumed density of PG of 2.3 g/cm^3. [30] (The approach to estimate the stack

[29] State of Florida, "Florida Gypsumstacks."

[30] U.S. EPA, Region 4, Superfund Division, "Engineering Evaluation/Cost Analysis: Closure of the East Gypsum Stack and North Ponds, Mississippi Phosphates Corporation Site, Pascagoula, Jackson County, Mississiee i."

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volume was derived from EPA and Florida Department of Environmental Protection sources. [31]) Finally , since the Florida dataset uses data in metric units , we convert square meters into acres. Thus, we conclude that one acre contains approximately 850,000 tons of PG. We then divide the tota l tons of PG reused in 2039 for the lower- and upper•bound estimates by 850,000 to obtain the equivalent number of acres, multiply it by the actual cost per acre ($120,000), and present the NPV using three and seven percent discount rates.

In t his re port, based on the estima te d reused PG from 2020-2039, we assume that a PG stack of 97 acres is closed in 2039 for the lower-bound scenario and a PG stack of 290 acres is closed in 2039 for the uppe r-bound scenario.

Stack Expansion Costs

To estimate the potential cost savings from stack expansion, we first divide the weight of PG reused per yea r by 850,000 to conve rt it into acres. We then multiply the resulting quotient by $230,000, which is the cost to expand one acre. Fina lly, we discount the costs using three and seven percent rates.

Stack Maintenance and Water Management Costs

To est imate the pote ntial cost savings from stack ma inte na nce and water manag ement , we first multiply the sum of the annual weight of PG reused (in tons) plus the weight of PG reused in previous years by $0.03. We then calculate the NPV for the enti re period of analysis using three and seven pe rcent discount rates .

Transportation Costs to Reuse Location

We assume that PG transportation costs are essentially the same as the cost of transporting alternative materials; therefore , from a social cost perspective , there is no marginal savings by transporting PG or another aggregate. This leads to the conclusion that there are no potential benefits related to savings from transporta tion costs. Thus, transportation costs are not shown in Table 9 conside ring that they are zero.

Table 7 provides the key assumptions for PG reuse used in the analysis .

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[31] Florida Department of Environmental Protection, "Aorida Gypsumstacks, Phosphogypsum Stack System Layer."; U.S. Environmental Protection Agency, "Nat ional Emission Standards for Hazardous Air Pollutants; National Emissions Standards for Radon Emissions from Phosphogypsum Stacks; 40 CFR Part 61 , " 13-19; and Appendix B.

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Table 7: Key Assumptions for PG Reuse Scenario

ITEM	LOWER-BOUND SCENARIO	UPPER-BOUND SCENARIO
PG reused In 2020	5% of annual production	1 0% of annual production
PG reused In 2021	5% of annual production	15% of annual production
PG reused In 2022	7.5% of annual production	20% of annual production
PG reused In 2023	7.5% of annual production	25% of annual production
PG reused in 2024	10% of annual production	30% of annual production
Year in which stack closure occurs	2039	2039
Conversion rate for PG (tons Into acres)	850,000	**850,000**

Results of Cost Savings from PG Reuse

Table 8 shows the total NPV of baseline costs associated with managing PG stacks, which range between $0.88 billion and $1.3 billion at seven and three percent discount rates, respectively.

Table 8: NPV of Baseline Costs to Manage PG

CATEGORY	NPV USING A 3% DISCOUNT RATE (IN$ MILLIONS)	NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)
Baseline Costs	**1,300**	**880**

The total NPV of cost savings between 2020-2042 is presented in Table 9. It shows savings associated with PG reuse ranging between $37 million and $52 million for the lower-bound scenario and $110 million and $160 million for the upper-bound scenario, using seven and three percent discount rates, respectively. It also presents the estimated cost savings for stack closure, water and maintenance management, expansion, and transportation costs. The largest savings result from the deferred stack expansion costs, with the second-largest savings a result of deferred stack closures.

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Table 9: NPV of Cost Savings from PG Reuse

COST CATEGORY[32]	LOWER-BOUND SCENARIO	LOWER-BOUND SCENARIO	UPPER-BOUND SCENARIO	UPPER-BOUND SCENARIO
	NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 7% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 3% DISCOUNT RATE (IN $ MILLIONS)	NPV USING A 7" DISCOUNT RATE (IN $ MILLIONS)
Closure Cost Savings	11	10	33	32
Water and Stack Management Costs	22	13	65	37
Expansion Costs	19	13	57	38
Total Cost Savings	52	37	160	110

Executive Order 13771 Deregulat ory Savings

Under E.O. 13771, EPA's action to allow PG to be reused as a road construction material would constitute a deregulatory action and would generate savings that could help EPA achieve its regulatory allocation.

Assuming that EPA either changes its existing regulation to allow a regulatory exemption for PG reuse in road construction or gives a one-time , broad approval of a petition for road construction reuse, EPA's action would constitute a deregulatory action under E.O. 13771. The Office of Management Budget's i mplementingmemor andum for E.O. 13771 draws the distinction between routine regulatory actions and one-time actions that produce on-going savings. Agency actions that require regular agency approvals - e.g., quotas, permits - are not deregulatory actions under E.O. 13771. However, if EPA's approval of PG petitions does not require further approvals, is not conditioned on satisfying reporting requirements, and is broadly applicable to PG producers, it would likely qualify as a deregulatory action. EPA then could count it as part of meeting E.O. 13771 's ratio of one deregulatory action for every two regulatory actions.

The action would also generate deregulatory savings. Under E.O. 13771, agencies are granted a regulatory allocation for each fiscal year. [33] The regul atory costs of significant economic regulatory actions and the deregulatory savings must add up to less than the agency's allocation. Agencies must align the savings and costs in the same fiscal year; in this case, the deregulatory savings from allowing PG reuse occur in future years. Table 10 gives the

[32] Transportation costs are omitted from the table as they are zero. Potent ial revenue obtained from selling PG is not estimated in this report.
[33] "Executive Order 1Jn1 of Ja nuary 30, 2017, Reducing Regulat ion and Controlling Re gulato ry Costs."

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estimated annual savings for the next five years, an illustrative period to demonstrate how savings increase in the near-term before reaching a relatively constant value.

Table 10: Estimated Cost Savings from 2021-2025

TOTAL COST SAVINGS (IN MILLIONS $)	2021	2022	2023	2024	2025
At 3 and 7 Percent Discount Rate	1.1-3.2	1.7-4.5	1.8-5.8	2.4-7.2	2.6-7.7
At 7 Percent Discount Rate	1.1-3.2	1.7-4.5	**1.8-5.8**	2.4-7.1	**2.6-7.6**

Summary

In summary, the analysis shows that the potential regulatory cost savings of changes that would allow the reuse of PG ranges between $37 million and $160 million. These results represent the NPV of savings for the period of analysis (2020-2042). These results strongly support the reuse of PG for beneficial applications such as road construction in the U.S. - applications already permitted and used in Europe and elsewhere. Additionally, they support the idea that using PG for road construction offers the possibility of significant savings not only to PG producers, but also to state transportation agencies to the extent they replace a percentage of the aggregates currently used for road construction with PG.

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APPENDIX 1

1. Current producers of phosphoric acid/phosphogypsum (PG) in the U.S., including annual PG production, per stack. If PG production is not available, what is the annual phosphoric acid production (weight)?

Production Company Identifier	**2018 Production** Amount: **PG (T/stack)** - Phosphoric **Acid** (T/year)	**2017** Production Amount: **PG (T/stack)** - Phosphoric **Acid** (T/year)	**2016** Production Amount: PG (T/stack) - **Phosphoric Acid** (T/year)	Information Provided: **PG or** Phosphoric **Acid?**
[Enter response]	[Enter response]	[Enter response]	[Enter response]	[Enter response]

2. Number of PG stacks your company manages and the approximate weight of PG stored in each stack as of 12/31/18. Include those stacks that are inactive, but that have not been closed. Do not include stacks that are permanently closed (not good candidates for PG reuse).

Production Company Identifier	**Approximate Weight of PG Stored** in **Each Stack (T/stack)**	**Stack Status (Active/ Inactive)**
[Enter response]	[Enter response]	[Enter response]

3. With a focus on the process of PG stacking, and an emphasis on active stacking disposal **areas,** for each active stack, please include the annual costs for: (a)Transporting the gypsum from the phosphoric acid facility to the stack (b)Stack maintenance, including labor costs and monitoring, inspection, reporting requirements (c)Stack process water management, including water balancing and water treatment.

Phosphoric Acid Facility	**(a)** Annual **Gypsum Transportation Cost ($/year)**	**(b) Stack Maintenance Cost ($/year)**	(c) **Stack Process Water Management Cost ($/year)**	**Year** in **which Costs Are Provided (e.g., $2019 Dollars)**
[Enter response)	[Enter response]	[Enter response]	[Enter response]	[Enter response]

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4. Please identify longer term (next five years in aggregate) stack closure costs on a per acre basis (include the costs associated with long term water inventory management)

Phosphoric Acid Company	Stack Closure Management Costs [2020-2024] ($/acre)	Water Inventory Management Costs [2020-2024] ($/acre)	Stack Expansion Costs [2020-2024] ($/acre)	Year in which Costs Are Provided (e.g., $2019 Dollars)
[Enter response]	[Enter response}	[Enter response]	[Enter response]	[Enter response]

ED_005285_00000990-00027

February 2020

Location of Phosphogypsum Stacks

Mosaic:

Plant City: 660 E. County Line Road, Plant City, FL 33565

Bartow: 3200 Hwy 60 W, Bartow, FL 33830

South Pierce: 7450 County Road 630, Mulberry, FL 33860

Riverview: 8813 Hwy 41 S, Riverview, FL 33578

Green Bay: 4390 County Road 640 W, Bartow, FL 33830

New Wales: 3095 Hwy 640 W, Mulberry, FL 33860

Uncle Sam: 7250 Hwy 44, Uncle Sam, LA 70792\

Simplot:

Simplot Phosphates LLC
[HYPERLINK "x-apple-data-detectors://1/1" \h][HYPERLINK "x-apple-data-detectors://1/1" \h]

Simplot Don Plant
1150 W Highway 30
Pocatello, Idaho 83204

Nutrien:

White Springs Plant
15843 SE 78th Street
White Springs, Florida 32096

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/19/2020 8:18:07 PM
To: Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: TFI Media Tracker
Attachments: TFI Media tracker.xlsx

Hi Jess,

I've pulled together the attached media tracker related to the TFI press release. Please let me know if you have any comments on the content. I will plan to share this with Lee by COB.

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/15/2020 12:57:31 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: Approval of Other Use of Phosphogypsum: Supporting Documents Webpage Requires Your Review and Approval

I think so. If you have any problems getting it, I can create you a PDF.

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 8:56 AM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Approval of Other Use of Phosphogypsum: Supporting Documents Webpage Requires Your Review and Approval

Do I need to be in the VPN for this?

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Wednesday, October 14, 2020 11:32 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: Approval of Other Use of Phosphogypsum: Supporting Documents Webpage Requires Your Review and Approval
Importance: High

Dear Jon, Dan, and Tom:

I created a document page with the supporting materials that will appear in the Docket upon publication. It includes a signed copy of Administrator Wheeler's letter, as TFI told Lee they had no problem with our putting on the website. Please review the page to ensure I got everything right, and provide me with any edits. We need to publish this tomorrow morning to answer the press inquiry due at 11 AM. (It will enable us to quickly answer or even avoid further inquiries).

The page link is below. You will need to log-in with your LAN ID and password.

Ex. 5 Deliberative Process (DP)

One document is missing: I need RPD's Review of the Risk Assessment. Please provide that to me as soon as it ready for release.

Thanks for all your help with this.

Tony Nesky
Center for Radiation Information and Outreach
Tel: 202-343-9597
nesky.tony@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 4/13/2020 11:42:37 AM
To: Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: Responses to latest TFI documents

Hi Joe,

One more option if you think it would be helpful, we could try to convert the PDF to a word document if you'd like for people to comment directly in the document. This generally works well, but there are a few snags that I've ran into before that would prevent us from being able to do this. This is another thing we can talk about during today's admin call if you think it would be something worth looking in to.

Thanks!
Stefanie

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Friday, April 10, 2020 5:52 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Nagata, Jonathan <Nagata.Jonathan@epa.gov>; Santillan, Eugenio-Felipe <santillan.eugenio-felipe@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>
Subject: Responses to latest TFI documents

I've uploaded the documents that TFI sent us to a folder on Sharepoint. I tried to set it up so that you could comment directly on the submissions, but sharepoint for now doesn't allow commenting on pdfs (we would have to add comments and then re-upload each individual commented version separate). For now, I've created two word documents: a general questions document, and a modeling specific questions document. Please add each of your comments/questions under a header for yourself (e.g. Phil, Dave, Joe, etc), the document it came from, and page #. As they get populated I'll look through and can revise the commenting strategy as needed (for example if we want to create a comment document for each document from TFI). Here's the link:

Ex. 5 Deliberative Process (DP)

Make sure to select autosave so that others can be aware of your work while you're adding comments.

Let me know if I can answer any questions.

Best,

Joe

-----Original Appointment-----
From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Wednesday, April 8, 2020 11:20 AM
To: Veal, Lee; Peake, Tom; Schultheisz, Daniel; Diaz, Charlene; Wieder, Jessica; Egidi, Philip; Rustick, Joseph; Bacon, Stefanie; Nagata, Jonathan; White, Rick; Santillan, Eugenio-Felipe; Lee, Raymond
Cc: Stuenkel, David; David Stuenkel
Subject: TFI risk assessment review - recurring technical meeting

When: Wednesday, April 8, 2020 11:00 AM-12:00 PM (UTC-05:00) Eastern Time (US & Canada).
Where: Skype/phone only

Updated with answers to suggested questions:

When should people get comments in? – **4/15/20, for next week's call**
What should people focus on? – **Was TFI responsive to our questions**
Who should be the arbiter of TFI's responses to our questions? All, you, Dave S? – **Group review next week**
Should Phil have SCA look at the report now or wait for us? – **Pause one week**

Ex. 5 Deliberative Process (DP)

Join Skype Meeting

Trouble Joining? Try Skype Web App

Join by phone

Toll number: **Ex. 6 Personal Privacy (PP)** English (United States)

Find a local number

Conference ID: Ex. 6 Personal Privacy (PP)

Forgot your dial-in PIN? | Help

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 9/8/2020 6:33:42 PM
To: Shogren, Angela [Shogren.Angela@epa.gov]; Aquino, Marcos [Aquino.Marcos@epa.gov]
CC: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: Other Uses of Phosphogypsum

Hi Marcos,

Currently, there are no completed and approved applications for other uses of phosphogypsum; therefore, there is no supporting documentation available on our website. In the past there have been several incomplete applications submitted to the Agency. Ultimately, those applications were all withdrawn. I am not aware that the documentation for those withdrawn applications is publicly available. I have copied those who may know more.

Note that The Fertilizer Institute has submitted a request for the Agency to review an other use of phosphogypsum. This request is currently under review and a decision on the request has not been finalized by the Agency.

I hope this is helpful,
Stefanie

From: Shogren, Angela <Shogren.Angela@epa.gov>
Sent: Tuesday, September 8, 2020 1:29 PM
To: Aquino, Marcos <Aquino.Marcos@epa.gov>
Cc: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Other Uses of Phosphogypsum

Hi Marcos,

I've copied Stefanie here and she can help put him in touch with someone in our office. I'm not sure who the best contact is at this point – Dan? Phil?

Stefanie will know ☺

Angela Shogren | Public Affairs Specialist
U.S. Environmental Protection Agency

P: (202) 343-9761 | E: shogren.angela@epa.gov

From: Aquino, Marcos <Aquino.Marcos@epa.gov>
Sent: Tuesday, September 8, 2020 1:15 PM
To: Shogren, Angela <Shogren.Angela@epa.gov>
Subject: FW: Other Uses of Phosphogypsum

Help!

Do you have anything to help this gentleman? Please let me know.

Regards,

Marcos Aquino
Radiation Program Manager
Acting Chief
Partnership Programs and Grants Branch
Air Protection Division
US EPA Region 3
1650 Arch Street
Philadelphia, Pennsylvania 19103
(215) 814-3422 office
(215) 514-8357 mobile
aquino.marcos@epa.gov
https://www.epa.gov/radtown

From: Faas, Nicholas M. <nfaas@jonesday.com>
Sent: Tuesday, September 08, 2020 1:06 PM
To: Aquino, Marcos <Aquino.Marcos@epa.gov>
Subject: Other Uses of Phosphogypsum

Hi Marcos,

Thanks for taking my call. As mentioned, I am looking for previously-submitted publicly available applications for "other uses" of phosphogypsum. The guidance available on EPA's website (https://www.epa.gov/sites/production/files/2015-05/documents/guidance.pdf) states:

> **How can I find out if there is an earlier application someplace that is similar enough to mine I could use its risk assessment?**
> All applications that may be released to the public will be included in this Web page. You may also contact us at **radiation.questions@epa.gov** if you need additional information.

I have not been able to find the web page referred to in the guidance document. I have not yet emailed radiation.questions@epa.gov, but can do so as a next step if you're also unable to find anything.

Thanks so much for your help.

Warm regards,
Nick

Nicholas M. Faas (Nick)
Associate

JONES DAY® - One Firm Worldwide℠
500 Grant Street, Suite 4500
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nfaas@jonesday.com

This e-mail (including any attachments) may contain information that is private, confidential, or protected by attorney-client or other privilege. If you received this e-mail in error, please delete it from your system without copying it and notify sender by reply e-mail, so that our records can be corrected.

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 8/31/2020 7:03:34 PM
To: Stevens, Katherine [stevens.katherine@epa.gov]
CC: Jones, Enesta [Jones.Enesta@epa.gov]
Subject: TFI Communications Plan
Attachments: TFI Communications Plan_8-31.docx

Good afternoon Kati and Enesta,

I wanted to provide an update on our draft (but nearly final) communications plan for The Fertilizer Institute (TFI). As a reminder, this communications plan relates to Agency action on The Fertilizer Institute (TFI)'s application for alternative uses of phosphogypsum. I mentioned earlier in the month that final Agency action is currently pending management and legal review; this is still true, but I anticipate we are more like days away from a final decision timeline, rather than weeks.

Attached is a draft copy of the communications plan that the RPD and ORIA management are currently reviewing. I wanted you to have this advance copy of the communications plan so that you knew what we were working on. I will provide another update once the plan has been finalized internally.

Also, we also heard that TFI does not intend to do a press release for a while, maybe when they get a project it will be appropriate. We thought this would be important for you to know.

Please let me know if you have any questions,
Stefanie

Message

Ex. 5 Deliberative Process (DP)

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 12/4/2019 4:00:49 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]
Subject: TFI Comms Plan

Ex. 5 Deliberative Process (DP)

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 11/29/2019 8:27:58 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: Draft TFI Webpage Content
Attachments: TFI website.docx

Good afternoon Jon,

I hope you had a nice Thanksgiving with your family!

Attached is draft web content for the TFI page. I'd like to spend some time discussing this draft content with you next week. I'll be out Monday & Tuesday, but hope we can find some time later in the week. The proposed web content is due to Lee by 12/6.

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/16/2020 3:07:53 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Thanks Tony!

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Friday, October 16, 2020 10:57 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

It's on the website now at
https://www.epa.gov/sites/production/files/2020-10/documents/attachment_a_-_road_specs.pdf

I tried to upload it yesterday, but apparently the upload failed. Thanks for catching this!!!

Tony

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Friday, October 16, 2020 10:41 AM
To: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: FW: Please try to get the final edits/review of the technical review done by around 2 pm

Tony,

Is this attachment on our supporting docs page? I cross walked what Ray has queued up for the docket, and what is on our website, and I couldn't figure out if we missed this one.

Would you mind taking a look. Thanks in advance for double checking,
Stefanie

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Thursday, October 15, 2020 5:24 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Hi Stef,

Ahh, my apologies for the miswording/confusion – I have 9 appendices, plus the Attachment A of Road Specs. Not sure why I lumped them all together.

Just for reference, that attachment is tagged onto this e-mail.

Thanks,

Ray

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, October 15, 2020 3:47 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Hi Ray,

I compared the documents Ray listed as being added to the docket and the items Tony has posted to our supporting documents page. It looks like all documents listed on our web page have also been queued up to be on the docket. I only have one question:

Tony & Ray: Is there an additional TFI appendix? Ray mentioned 10 are in the docket. Our website has 9.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 2:29 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

I just learned from Lee that Jon E is Ok with the report, but Andrea is still looking at it. However, Lee wants Charles to look at it just to make sure there are not any legal issues.

So, Jon, when you send out the document in a few minutes, please include Charles on the distribution.
Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Thursday, October 15, 2020 2:26 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Hi all,

All supporting documentation I've received (a total of 15 documents – the PG Risk Assessment Review [plus 10 appendices], the April TFI petition, 1992 BID, memo for road abandonment, and signed letter from the Administrator)

has been processed and uploaded into the docket. Again, the number in regulations.gov is:

EPA-HQ-OAR-2020-0442

As Jon sent out to us, the FR will be published on 10/20. That's plenty of time for the docket staff to do their final QA, so there should not be any issues.

Let me know if I've missed anything or if there are any additional docs we need to have in there in the meantime.

Thanks again all,

Ray

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Thursday, October 15, 2020 11:55 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

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From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 11:50 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

And to Ray, so he can put it in the docket.

From: Schultheisz, Daniel
Sent: Thursday, October 15, 2020 11:32 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Cc: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

Can you send Tony the 1992 BID? We should probably put it on the web site.

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Thursday, October 15, 2020 11:31 AM
To: Peake, Tom <Peake.Tom@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Please try to get the final edits/review of the technical review done by around 2 pm

On it now.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, October 15, 2020 10:40 AM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: Please try to get the final edits/review of the technical review done by around 2 pm

Jon,
I hope the kid situation is under control now.

Lee seemed to be OK with the changes to the document I made so please verify that I did not make any misstatements and incorporate Dan's edits. I know you won't be able to get to it until around noon, but there should not be much to do.

There is a push to get everything loaded onto the web as soon as possible, so can you try to get the final technical review document in a revised Word document and in a pdf document by around 2 pm to us?

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 9/24/2020 6:28:00 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: RE: Two versions of Subpart R page: one for publication prior to Federal Register Notice (if desired) and one for publication after the Federal Register Notice appears.

Thank you ☺

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Thursday, September 24, 2020 1:02 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Two versions of Subpart R page: one for publication prior to Federal Register Notice (if desired) and one for publication after the Federal Register Notice appears.

Good catch! I made the changes.

Tony

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, September 24, 2020 9:31 AM
To: Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Two versions of Subpart R page: one for publication prior to Federal Register Notice (if desired) and one for publication after the Federal Register Notice appears.

Hi Tony,

Thank you for making the two pages. I really like how the page referring to the future FR notice reads ☺

Ex. 5 Deliberative Process (DP)

Thank you again for the quick turn around pulling together the draft pages.

Stefanie

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Wednesday, September 23, 2020 5:12 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: Two versions of Subpart R page: one for publication prior to Federal Register Notice (if desired) and one for publication after the Federal Register Notice appears.
Importance: High

Dear Stefanie:

Here are two versions of the updated Subpart R page. If they don't want to wait to update the webpage until the Notice is published in the Federal Register, then management will have to approve Version 1. If they want to wait until the Notice is published in the Federal Register, than Version 2 can be published without further review, but I need the signature date and URL of the Notice.

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Tony Nesky
Center for Radiation Information and Outreach
Tel: 202-343-9597
nesky.tony@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 8/25/2020 7:24:26 PM
To: Colip, Matthew [colip.matthew@epa.gov]
Subject: The Fertilizer Institute | Communications Plan

Hi Matt,

I am finalizing a communications plan for an impending Agency action related to the approval of an alternative use of phosphogypsum in government road construction projects. We are expecting the Agency to approve The Fertilizer Institute's request to allow incorporation of this material in road beds. This approval should be announced in a matter of days.

In my communications plan, I would like to include a contact for OLEM, just in case anyone in the EPA management chain needs to reach back. Kati Stevens suggested I reach out to you for a contact. Do you happen to have someone I could include?

Thank you,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/15/2020 7:48:07 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: EPA-2021-000305 Coordination Memo

This is the first time I've laughed today ☺ Thanks Dan!

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 3:44 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

I don't think years have any meaning anymore.

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Thursday, October 15, 2020 3:44 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

Oh oops! Read that year wrong.

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, October 15, 2020 3:36 PM
To: Nesky, Anthony <Nesky.Tony@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

The starting date is 10/15/2019 (a year ago), about when TFI submitted its initial request.

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Thursday, October 15, 2020 3:33 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

We will be sending a response to the Center for Biodiversity via the Press Office, with a link to all the documents on the website. Let's get that out the door and then see if they still are interested in the FOIA.

Tony

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Thursday, October 15, 2020 3:30 PM

To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: FW: EPA-2021-000305 Coordination Memo

Hi Jon/all,

We just got this incoming request from Ann Brown over at the Center for Biological Diversity. It's a bit odd, because she's asking for documentation surrounding the FR notice & letter that was signed yesterday...but specifically any records starting on today's date (10/15) through the time we actually conduct the search? I'm not exactly sure what's she's looking for with that date range, aside from the correspondence of us getting all of the supporting materials together.

I know you talked to Jacki Lopez the other day. Do you think they are just looking to get the docketed materials sooner? Actually, the website is up now so all of the documents that will be docketed should be up there as well.

Thoughts? Should one of us give CBD a call/email?

Thanks,

Ray

From: Hamilton, Sabrina <Hamilton.Sabrina@epa.gov>
Sent: Thursday, October 15, 2020 3:21 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>; Marbury, Candice <Marbury.Candice@epa.gov>
Subject: FW: EPA-2021-000305 Coordination Memo

Ray,

This FOIA will be assigned to ORIA sometime today. Thanks

Sabrina Hamilton

Sabrina Hamilton
Air and Radiation Liaison Specialist
and FOIA Coordinator
Office of Air and Radiation
U.S. Environmental Protection Agency (EPA)
1200 Pennsylvania Avenue, N.W. (6101-A)
Washington, D.C. 20460
Tel: (202) 564-1083

From: Hamilton, Sabrina
Sent: Thursday, October 15, 2020 3:17 PM
To: Davis, Gail <Davis.Gail@epa.gov>; Ingram, Earl <Ingram.Earl@epa.gov>; Malloy, Marilyn <Malloy.Marilyn@epa.gov>
Cc: Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Marbury, Candice <Marbury.Candice@epa.gov>; Lubetsky, Jonathan <Lubetsky.Jonathan@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

Gail,

Yes, this is OAR's FOIA. Please assign. Thanks

Sabrina Hamilton

Sabrina Hamilton
Air and Radiation Liaison Specialist
and FOIA Coordinator
Office of Air and Radiation
U.S. Environmental Protection Agency (EPA)
1200 Pennsylvania Avenue, N.W. (6101-A)
Washington, D.C. 20460
Tel: (202) 564-1083

From: Davis, Gail <Davis.Gail@epa.gov>
Sent: Thursday, October 15, 2020 3:12 PM
To: Ingram, Earl <Ingram.Earl@epa.gov>; Malloy, Marilyn <Malloy.Marilyn@epa.gov>; Hamilton, Sabrina <Hamilton.Sabrina@epa.gov>
Cc: Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

Thank you Earl.

From: Ingram, Earl <Ingram.Earl@epa.gov>
Sent: Thursday, October 15, 2020 3:06 PM
To: Davis, Gail <Davis.Gail@epa.gov>; Malloy, Marilyn <Malloy.Marilyn@epa.gov>; Hamilton, Sabrina <Hamilton.Sabrina@epa.gov>
Cc: Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>
Subject: RE: EPA-2021-000305 Coordination Memo

Gail.

This is an office of Air and Radiation Request. You will need to check with them. The link to the FR Notice is below. EPA-HQ-OAR-2020-0442; FRL–10014-36-OAR

https://www.epa.gov/sites/production/files/2020-10/documents/federal_register_text_of_neshap_subpart_r_approval_tfi_request_other_use_phosphogypsum.pdf

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From: Davis, Gail <Davis.Gail@epa.gov>
Sent: Thursday, October 15, 2020 3:02 PM
To: Malloy, Marilyn <Malloy.Marilyn@epa.gov>; Ingram, Earl <Ingram.Earl@epa.gov>; Hamilton, Sabrina <Hamilton.Sabrina@epa.gov>
Cc: Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>
Subject: EPA-2021-000305 Coordination Memo

This is a National FOIA Office Intake Coordination for the above-mentioned FOIA request. A copy of the request is attached. Please review the attachment to determine if the request has enough information for your office to process

under the FOIA. Please reply with one of the options below and by filling-in the requested information **no later than 5:00 pm your time on the next working day**.

NFO Preliminary Intake Review

[ ] The request is not reasonably described – clock not started – See Regulations at 40 C.F.R. 2.102(c)
[ ] The request is reasonably described – clock started – request may need additional clarification
NFO Notes: I wasn't sure if OAR or OCSPP would have responsive records for the attached request. Your guidance is appreciated.

FOIA Program Preliminary Intake Coordination (please complete)

1. [ ] **The request is not reasonably described.** My FOIA Program does not have enough information at this time to identify and locate the records. I understand the NFO will schedule a conference call with the FOIA requester. Our Program would like to be a part of the call: YES [ ] or NO [ ]
   - What additional information is necessary to process this request? (e.g. subject matter, date range, internal or external correspondence):
   - If YES, point of contact from your Program to attend the call:
   - If YES, what are the preferred dates and times to attend the call:

2. [ ] **The request is reasonably described**. My FOIA Program has enough information at this time to identify and locate the records.
   a) [ ] Please assign to my FOIA Program - additional clarification may be handled by my program.
   b) [ ] We would like the NFO's assistance in seeking additional clarification. Please stop the clock and schedule a conference call with the FOIA requester. Our Program would like to be a part of the call: YES [ ] or NO [ ]
      - What additional information is necessary to process this request? (e.g. subject matter, date range, internal or external correspondence):
      - If YES, point of contact from your Program to attend the call:
      - If YES, what are the preferred dates and times to attend the call:

3. [ ] **The request does not relate to work in my program.** Please assign to another FOIA Program or agency.
   - Suggested FOIA Program/agency if known:

4. [ ] OPTIONAL: The request can be responded to, **in part,** with **publicly available** or **previously released records**. The records are available at: *[INSERT LINK HERE].* ***If the publicly available or previously released records fully respond to the request, then the Program Office should prepare the close out letter with information to assist the requestor in retrieving the requested records.***
5.
   - [ ] The enclosed records fully respond to the request; *OR*
   - [ ] The enclosed records partially respond to the request.

If you have any questions about this NFO Intake Coordination, please contact me.

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 8/11/2020 5:31:31 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]
CC: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: RE: Draft TFI Webpage

Thank you for the review Joe!

Ex. 5 Deliberative Process (DP)

I would like to send the proposed web language to Jess later today so that she can have eyes on what we are thinking.

Thanks everyone!
Stefanie

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Tuesday, August 11, 2020 12:53 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Draft TFI Webpage

Hi Stefanie,

I think everything in general looks great. There are two minor suggestions I could think of, but neither I think would be necessary.

Ex. 5 Deliberative Process (DP)

Best,

Joe

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, August 11, 2020 10:10 AM
To: Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: Draft TFI Webpage

Thank you ☺

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Tuesday, August 11, 2020 10:08 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Draft TFI Webpage

Ok will do after my 10am meeting.

-Joe

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, August 11, 2020 10:07 AM
To: Rustick, Joseph <rustick.joseph@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: Draft TFI Webpage

Jon and Joe,

Could you please put eyes on the web language I am proposing be added to our Subpart R page. Please see below for the additional language, or attached for how the additional language would look within the context of the existing webpage. Yellow highlighting = placeholder text that will need to be updated. Please provide any feedback, I would like to send this to Jessica for review as soon as possible given our timeline on this project.

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Thanks,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/21/2020 1:29:53 PM
To: Hellberg, Dennis [Hellberg.Dennis@epa.gov]
Subject: FW: EPA Approval of Request for Other Use of Phosphogypsum
Attachments: TFI FR Notice 10-20-2020.pdf; Fertilizer.Institute.SIGNED.pdf

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From: Bacon, Stefanie
Sent: Tuesday, October 20, 2020 8:58 AM
To: Ruth McBurney <rmcburney@crcpd.org>; Mendy Cremeans <mcremeans@crcpd.org>
Subject: EPA Approval of Request for Other Use of Phosphogypsum

Good morning Ruth and Mendy,

During our last board call, I mentioned an upcoming EPA action related to phosphogypsum. Now that it is official, I wanted to let you know that on October 14, EPA approved a request by The Fertilizer Institute (TFI) for use of phosphogypsum in government road construction projects. This approval is granted under the Clean Air Act and the provisions in 40 CFR 61.206, which allow EPA to approve other uses of phosphogypsum if they can be demonstrated to be at least as protective as keeping the material in a stack, which is the designated management method.

This approval is subject to terms and conditions, and we are not aware of any such projects under consideration at this time. A government agency proposing to use phosphogypsum in this manner would have to submit additional information to EPA and provide an opportunity for the public to review the proposal and documents related to this approval, including the risk assessment submitted by TFI. A key condition is that the road not be abandoned or converted for non-road uses, unless additional risk analyses are conducted and EPA is notified.

Attached are the approval letter and the Federal Register notice, which was published today. You can find more information at https://www.epa.gov/radiation/subpart-r-national-emission-standards-radon-emissions-phosphogypsum-stacks. The official docket for this action can be accessed through www.regulations.gov, search for Docket No. EPA-HQ-OAR-2020-0442.

Please let me know if you have any questions. Thanks.
Stefanie

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/20/2020 1:24:17 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]
CC: Peake, Tom [Peake.Tom@epa.gov]
Subject: RE: Approval of Request for Other Use of Phosphogypsum

My apologies, I apparently am behind! Glad this is ready to go live ☺

From: Nesky, Anthony <Nesky.Tony@epa.gov>
Sent: Tuesday, October 20, 2020 9:22 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>
Subject: RE: Approval of Request for Other Use of Phosphogypsum

It's been reviewed and ready to go public. The FR Notice is out, but the Docket isn't yet open. As soon as the Docket opens, I'll update all relevant pages, and the document page will include our Review.

TOny

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Tuesday, October 20, 2020 9:20 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Approval of Request for Other Use of Phosphogypsum

Tony can correct me, but as of yesterday, we were waiting to receive the technical review. Jon expected that we would receive it soon, but we can't post it until we have it (and have permission for it to go public).

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Tuesday, October 20, 2020 9:06 AM
To: Diaz, Charlene <diaz.charlene@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: RE: Approval of Request for Other Use of Phosphogypsum

It would just save them some time searching, if they don't already have them. You can provide our website link, although it doesn't look like the technical review is posted yet (Tony, is that right?). As of about 8:30, the docket wasn't showing anything other than the FR notice. But the technical review will be on the website and the docket today.

From: Diaz, Charlene <diaz.charlene@epa.gov>
Sent: Tuesday, October 20, 2020 9:01 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>
Subject: RE: Approval of Request for Other Use of Phosphogypsum

Hi Dan,

I sent the link to the Regions that you provided this morning. Would you like for me to forward these documents to then as well? I know there was a request to receive the analysis document.

Thanks,
Charlene

Cordially,
Charlene L. Diaz

Charlene L. Diaz, MBA, MS
Special Assistant / RPP Regional Coordinator
Radiation Protection Division
Office of Radiation and Indoor Air
Office: (202) 564-8905
Fax: (202) 343-2304
Email: diaz.charlene@epa.gov

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Tuesday, October 20, 2020 8:46 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Subject: FW: Approval of Request for Other Use of Phosphogypsum

Here's what I sent ASTSWMO. Kerry Callahan is the ASTSWMO staff person we deal with for the Radiation Task Force, which is under the Materials Management Subcommittee. Feel free to edit as appropriate to make it CRCPD-specific.

I'd suggest having Charlene send anything to the regions. We did have a call yesterday and gave them an overview, and I think they might have the website.

From: Schultheisz, Daniel
Sent: Tuesday, October 20, 2020 8:29 AM
To: Kerry Callahan <KerryC@astswmo.org>
Subject: Approval of Request for Other Use of Phosphogypsum

Kerry:

You may have heard something about this, but I wanted to let you know that on October 14 EPA approved a request by The Fertilizer Institute (TFI) for use of phosphogypsum in government road construction projects. This approval is granted under the Clean Air Act and the provisions in 40 CFR 61.206, which allow EPA to approve other uses of phosphogypsum if they can be demonstrated to be at least as protective as keeping the material in a stack, which is the designated management method.

This approval is subject to terms and conditions, and we are not aware of any such projects under consideration at this time. A government agency proposing to use phosphogypsum in this manner would have to submit additional information to EPA and provide an opportunity for the public to review the proposal and documents related to this approval, including the risk assessment submitted by TFI. A key condition is that the road not be abandoned or converted for non-road uses, unless additional risk analyses are conducted and EPA is notified.

I thought this action would be of interest to the Materials Management Subcommittee, as states contemplating such use may have to conduct their own analyses to approve any such projects. EPA's approval is strictly limited to the Clean Air Act, and does not relieve TFI or end users of the responsibility to comply with any other applicable laws or regulations.

Attached are the approval letter and the Federal Register notice, which was published today. You can find more information at https://www.epa.gov/radiation/subpart-r-national-emission-standards-radon-emissions-phosphogypsum-stacks. The official docket for this action can be accessed through www.regulations.gov, search for Docket No. EPA-HQ-OAR-2020-0442.

Please let me know if you have any questions. Thanks.

Dan

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/20/2020 1:00:29 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: Approval of Request for Other Use of Phosphogypsum

Thank you Dan!

This was very helpful ☺ I edited the email to make it appropriate for CRCPD and just sent it over to them.

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Tuesday, October 20, 2020 8:46 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Subject: FW: Approval of Request for Other Use of Phosphogypsum

Here's what I sent ASTSWMO. Kerry Callahan is the ASTSWMO staff person we deal with for the Radiation Task Force, which is under the Materials Management Subcommittee. Feel free to edit as appropriate to make it CRCPD-specific.

I'd suggest having Charlene send anything to the regions. We did have a call yesterday and gave them an overview, and I think they might have the website.

From: Schultheisz, Daniel
Sent: Tuesday, October 20, 2020 8:29 AM
To: Kerry Callahan <KerryC@astswmo.org>
Subject: Approval of Request for Other Use of Phosphogypsum

Kerry:

You may have heard something about this, but I wanted to let you know that on October 14 EPA approved a request by The Fertilizer Institute (TFI) for use of phosphogypsum in government road construction projects. This approval is granted under the Clean Air Act and the provisions in 40 CFR 61.206, which allow EPA to approve other uses of phosphogypsum if they can be demonstrated to be at least as protective as keeping the material in a stack, which is the designated management method.

This approval is subject to terms and conditions, and we are not aware of any such projects under consideration at this time. A government agency proposing to use phosphogypsum in this manner would have to submit additional information to EPA and provide an opportunity for the public to review the proposal and documents related to this approval, including the risk assessment submitted by TFI. A key condition is that the road not be abandoned or converted for non-road uses, unless additional risk analyses are conducted and EPA is notified.

I thought this action would be of interest to the Materials Management Subcommittee, as states contemplating such use may have to conduct their own analyses to approve any such projects. EPA's approval is strictly limited to the Clean Air Act, and does not relieve TFI or end users of the responsibility to comply with any other applicable laws or regulations.

Attached are the approval letter and the Federal Register notice, which was published today. You can find more information at https://www.epa.gov/radiation/subpart-r-national-emission-standards-radon-emissions-phosphogypsum-stacks. The official docket for this action can be accessed through www.regulations.gov, search for Docket No. EPA-HQ-OAR-2020-0442.

Please let me know if you have any questions. Thanks.

Dan

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 10/14/2020 7:21:35 PM
To: Peake, Tom [Peake.Tom@epa.gov]
Subject: RE: Administrator digitally signed: The Fertilizer Institute (TFI) Phosphogypsum Letter & FR Notice

Tom,

I'm not sure, there was some talk this morning about sending it via email to TFI, but Millett would probably be the best person to check with.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, October 14, 2020 3:20 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: Administrator digitally signed: The Fertilizer Institute (TFI) Phosphogypsum Letter & FR Notice

Any idea whether TFI has seen it?

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Wednesday, October 14, 2020 3:17 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>; Nagata, Jonathan <Nagata.Jonathan@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Tong, Xinyue <Tong.Xinyue@epa.gov>; Santillan, Eugenio-Felipe <santillan.eugenio-felipe@epa.gov>; White, Rick <White.Rick@epa.gov>; Nesky, Anthony <Nesky.Tony@epa.gov>
Subject: FW: Administrator digitally signed: The Fertilizer Institute (TFI) Phosphogypsum Letter & FR Notice

FYI – includes the signed FR notice as well. No word yet on pub date but will keep you all posted.

From: Morgan, Ruthw <morgan.ruthw@epa.gov>
Sent: Wednesday, October 14, 2020 2:40 PM
To: Campbell, Ann <Campbell.Ann@epa.gov>
Cc: Pritchard, Eileen <Pritchard.Eileen@epa.gov>; Millett, John <Millett.John@epa.gov>; DeLuca, Isabel <DeLuca.Isabel@epa.gov>; Gaines, Cynthia <Gaines.Cynthia@epa.gov>; Shoaff, John <Shoaff.John@epa.gov>; Lubetsky, Jonathan <Lubetsky.Jonathan@epa.gov>; Mcquilkin, Wendy <Mcquilkin.Wendy@epa.gov>; Sandfoss, Kristina <Sandfoss.Kristina@epa.gov>
Subject: Administrator digitally signed: The Fertilizer Institute (TFI) Phosphogypsum Letter & FR Notice

Good afternoon,

Today, the Administrator digitally signed: The Fertilizer Institute: Phosphogypsum Letter and FR Notice.

If you have any questions about this email, please let me know. Thanks!

Ruthw Morgan, Special Assistant
Office of the Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Ave., NW
Washington, DC 20460
(202) 564-1326
Morgan.Ruthw@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 12/4/2020 6:51:13 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
Subject: FW: phosphogypsum updated pdf
Attachments: Phosphogypsum_risk_technical_summary_final_2020_clean - updated.pdf

Tony & Ray,

I have good news, the attached PDF has been cleared to be posted to the web and updated to the docket. Could you each please proceed with pulling back the previous version and posting the attached. Feel free to retitle the document as needed.

Thank you!
Stefanie

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Thursday, December 3, 2020 5:51 PM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: phosphogypsum updated pdf

Hi Steph,

Here's the final pdf with updated codes but no other formatting changes (other than the spacing and then I shifted Table 2 a little to make space to keep the footnotes on one page.)

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 12/3/2020 9:20:09 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
CC: Rustick, Joseph [rustick.joseph@epa.gov]; Nesky, Anthony [Nesky.Tony@epa.gov]
Subject: RE: EPA tech summary errata
Attachments: Phosphogypsum_risk_technical_summary_final_2020_clean - updated (PDF1).pdf

Jon/Joe/Tony,

Do you see any formatting errors in the attached TFI technical document? I believe I have fixed the discrepancies that Jon listed, but I would appreciate everyone take one last look before we post an updated version to the web and docket.

To be clear: please don't post this copy until we are all in agreement that it looks good ☺

Thanks,
Stefanie

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Monday, November 30, 2020 10:26 AM
To: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: EPA tech summary errata

Here is what I caught:

On p.5, in "Summary of Results", an error printed because the text refers to Table 1.

Footnotes for Table 2 bleed over the page

The final sentence of page 8 bleeds over, creating a nearly blank page.

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 4/1/2020 12:58:15 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]
Subject: TFI Communications Plan
Attachments: TFI Communications Plan.docx

Document available here **Ex. 5 Deliberative Process (DP)** and attached.

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 9/23/2019 3:01:39 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: Very Draft TFI Comms Plan
Attachments: TFI Communications Plan.docx

Jon,

Here's the basic communications plan that I've drafted for TFI. It was based on TFI briefing materials, but consider it still in very draft form. We can discuss today, and continue to modify as the TFI application moves forward.

Thanks,
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Bacon, Stefanie [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=A11E1BEA77424AA0AE0E2538AFCEF76A-GERA, STEFA]
Sent: 2/7/2020 12:44:48 PM
To: Bacon, Stefanie [Bacon.stefanie@epa.gov]
Subject: To Read
Attachments: PG Risk Assessment Review - 012720.docx

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Appointment

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 8/31/2020 2:56:30 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Emmerson, Caroline [Emmerson.Caroline@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; White, Rick [White.Rick@epa.gov]
CC: Coleman, Cheryl [Coleman.Cheryl@epa.gov]; Villamizar, Nicole [Villamizar.Nicole@epa.gov]; Chow, Rita [Chow.Rita@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]; Crossland, Andy [Crossland.Andy@epa.gov]; Elliott, Ross [Elliott.Ross@epa.gov]; Celeste, Laurel [celeste.laurel@epa.gov]; Mills, Jason [Mills.Jason@epa.gov]; Birchfield, Norman [Birchfield.Norman@epa.gov]; Atagi, Tracy [Atagi.Tracy@epa.gov]; Huff, Mark J [huff.markj@epa.gov]; Cory, Preston [Cory.Preston@epa.gov]; Harlow, David [harlow.david@epa.gov]; Dominguez, Alexander [dominguez.alexander@epa.gov]; Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Cook, Steven [cook.steven@epa.gov]; Hoskinson, Carolyn [Hoskinson.Carolyn@epa.gov]; Sullivan, Greg [Sullivan.Greg@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]

Subject: TFI request for alternative use of phosphogypsum
Attachments: ORCR_OAR Discussion Paper_Use of Phosphogypsum in Road Construction 9 14 2020 330 pm.docx; TFI approval letter on AD Letterhead Sept 11 ORCR Suggested Edits 9 14 2020.docx; OLEM OAR Agenda TFI Petition Approval Sept 15 2020 annotated 337 pm.docx
Location: Microsoft Teams Meeting

Start: 9/15/2020 2:00:00 PM
End: 9/15/2020 3:00:00 PM
Show Time As: Busy

Discussion with OLEM/ORCR

From: Emmerson, Caroline <Emmerson.Caroline@epa.gov>
Sent: Monday, August 31, 2020 9:56 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; White, Rick <White.Rick@epa.gov>; Coleman, Cheryl <Coleman.Cheryl@epa.gov>; Villamizar, Nicole <Villamizar.Nicole@epa.gov>; Chow, Rita <Chow.Rita@epa.gov>
Subject: RE: Introduction -- documents related to TFI request

Good morning Lee and Tom,

We expect to complete our review of the TFI documents by September 11. We can schedule a meeting with you the week of September 14 to discuss our concerns and questions.

Thanks,

Caroline

Appointment

From: Villamizar, Nicole [Villamizar.Nicole@epa.gov]
Sent: 9/1/2020 8:00:26 PM
To: Villamizar, Nicole [Villamizar.Nicole@epa.gov]; Emmerson, Caroline [Emmerson.Caroline@epa.gov]; Coleman, Cheryl [Coleman.Cheryl@epa.gov]; Chow, Rita [Chow.Rita@epa.gov]; Mills, Jason [Mills.Jason@epa.gov]; Birchfield, Norman [Birchfield.Norman@epa.gov]; Huff, Mark J [huff.markj@epa.gov]; Celeste, Laurel [celeste.laurel@epa.gov]; Crossland, Andy [Crossland.Andy@epa.gov]; Elliott, Ross [Elliott.Ross@epa.gov]; Huggins, Richard [Huggins.Richard@epa.gov]; Atagi, Tracy [Atagi.Tracy@epa.gov]; Sullivan, Greg [Sullivan.Greg@epa.gov]
CC: Radtke, Meghan [Radtke.Meghan@epa.gov]; Rubright, Tyler [Rubright.Tyler@epa.gov]; Young, Jessica [Young.Jessica@epa.gov]

Subject: TFI Request - Pre-meeting among ORCR
Attachments: RE: TFI Request - Pre-meeting among ORCR
Location: Microsoft Teams Meeting

Start: 9/3/2020 8:30:00 PM
End: 9/3/2020 9:15:00 PM
Show Time As: Busy

Purpose: Review and discuss concerns re: TRI package (pre-meeting in advance of the 9/10 meeting with Steven Cook)

Join Microsoft Teams Meeting

Ex. 5 Deliberative Process (DP) United States, Washington DC (Toll)

Conference ID: Ex. 5 Deliberative Process (DP)

Local numbers | Reset PIN | Learn more about Teams | Meeting options

By participating in EPA hosted virtual meetings and events, you are consenting to abide by the agency's terms of use. In addition, you acknowledge that content you post may be collected and used in support of FOIA and eDiscovery activities.

Appointment

From: Holden, Patricia [Holden.Patricia@epa.gov]
Sent: 9/15/2020 1:34:26 PM
To: Emmerson, Caroline [Emmerson.Caroline@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; White, Rick [White.Rick@epa.gov]
CC: Coleman, Cheryl [Coleman.Cheryl@epa.gov]; Villamizar, Nicole [Villamizar.Nicole@epa.gov]; Chow, Rita [Chow.Rita@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]; Crossland, Andy [Crossland.Andy@epa.gov]; Elliott, Ross [Elliott.Ross@epa.gov]; Celeste, Laurel [celeste.laurel@epa.gov]; Mills, Jason [Mills.Jason@epa.gov]; Birchfield, Norman [Birchfield.Norman@epa.gov]; Atagi, Tracy [Atagi.Tracy@epa.gov]; Huff, Mark J [huff.markj@epa.gov]; Cory, Preston [Cory.Preston@epa.gov]; Harlow, David [harlow.david@epa.gov]; Dominguez, Alexander [dominguez.alexander@epa.gov]; Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Cook, Steven [cook.steven@epa.gov]; Hoskinson, Carolyn [Hoskinson.Carolyn@epa.gov]; Sullivan, Greg [Sullivan.Greg@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]

Subject: TFI request for alternative use of phosphogypsum
Attachments: ORCR_OAR Discussion Paper_Use of Phosphogypsum in Road Construction 9 14 2020 330 pm.docx; TFI approval letter on AD Letterhead Sept 11 ORCR Suggested Edits 9 14 2020.docx; OLEM OAR Agenda TFI Petition Approval Sept 15 2020 annotated 337 pm.docx
Location: Microsoft Teams Meeting

Start: 9/15/2020 2:00:00 PM
End: 9/15/2020 3:00:00 PM
Show Time As: Tentative

Discussion with OLEM/ORCR

From: Emmerson, Caroline <Emmerson.Caroline@epa.gov>
Sent: Monday, August 31, 2020 9:56 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; White, Rick <White.Rick@epa.gov>; Coleman, Cheryl <Coleman.Cheryl@epa.gov>; Villamizar, Nicole <Villamizar.Nicole@epa.gov>; Chow, Rita <Chow.Rita@epa.gov>
Subject: RE: Introduction -- documents related to TFI request

Good morning Lee and Tom,

We expect to complete our review of the TFI documents by September 11. We can schedule a meeting with you the week of September 14 to discuss our concerns and questions.

Thanks,

Caroline

Message

From: Cherepy, Andrea [Cherepy.Andrea@epa.gov]
Sent: 10/14/2020 4:15:14 PM
To: Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]
CC: Diaz, Charlene [diaz.charlene@epa.gov]; Edwards, Jonathan [Edwards.Jonathan@epa.gov]
Subject: RE: Edits to RPD Transition Papers (due at Noon Wed.)

Thank you!

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Wednesday, October 14, 2020 11:00 AM
To: Cherepy, Andrea <Cherepy.Andrea@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Diaz, Charlene <diaz.charlene@epa.gov>; Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Subject: RE: Edits to RPD Transition Papers (due at Noon Wed.)

Andrea,

Attached are the revised transition papers for WIPP and TFI.

Most edits were straight-forward, so I accepted those in Word. I left in those with larger changes, and added responses to comments. I've attached clean copies as well.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Sent: Tuesday, October 13, 2020 11:56 PM
To: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Diaz, Charlene <diaz.charlene@epa.gov>; Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Subject: Edits to RPD Transition Papers (due at Noon Wed.)
Importance: High

Lee and Rick,

Ann C. and Betsy completed their review of the transition papers. Please respond to the questions in the TFI Phosphogypsum paper and confirm that you are comfortable with the remaining edits as soon as possible, and no later than Noon. Ann needs to send these papers on to OGC for review.

Thank you,
Andrea

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 10/14/2020 1:04:16 PM
To: Cherepy, Andrea [Cherepy.Andrea@epa.gov]
CC: Edwards, Jonathan [Edwards.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]
Subject: RE: SIGNED: TFI response on Phosphogypsum

Thank you

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Sent: Wednesday, October 14, 2020 9:04 AM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Edwards, Jonathan <Edwards.Jonathan@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: FW: SIGNED: TFI response on Phosphogypsum

Lee,

Here's the signed letter for your files.

Andrea

From: Campbell, Ann <Campbell.Ann@epa.gov>
Sent: Wednesday, October 14, 2020 9:00 AM
To: Idsal, Anne <idsal.anne@epa.gov>; Moor, Karl <Moor.Karl@epa.gov>; Raymond, Kelley <Raymond.Kelley@epa.gov>; Cory, Preston <Cory.Preston@epa.gov>; Harlow, David <harlow.david@epa.gov>; Dominguez, Alexander <dominguez.alexander@epa.gov>; Tardif, Abigale (Abbie) <Tardif.Abigale@epa.gov>; Landeene, Sarah <Landeene.Sarah@epa.gov>; Shoaff, John <Shoaff.John@epa.gov>; Lubetsky, Jonathan <Lubetsky.Jonathan@epa.gov>; Edwards, Jonathan <Edwards.Jonathan@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: SIGNED: TFI response on Phosphogypsum

FYA,

Ann (Campbell) Ferrio
Chief of Staff
Office of Air and Radiation
(202) 566-1370

Begin forwarded message:

> **From:** "Hackel, Angela" <Hackel.Angela@epa.gov>
> **Date:** October 14, 2020 at 8:56:11 AM EDT
> **To:** "Millett, John" <Millett.John@epa.gov>, "Block, Molly" <block.molly@epa.gov>, "Stevens, Katherine" <stevens.katherine@epa.gov>, "Johnson, Taylor" <Johnson.Taylor.C@epa.gov>, "DeLuca, Isabel" <DeLuca.Isabel@epa.gov>, "Grantham, Nancy" <Grantham.Nancy@epa.gov>, "Jones, Enesta"

<Jones.Enesta@epa.gov>, "McFaul, Jessica" <mcfaul.jessica@epa.gov>, "Drinkard, Andrea" <Drinkard.Andrea@epa.gov>
Cc: "Cory, Preston" <Cory.Preston@epa.gov>, "Tardif, Abigale (Abbie)" <Tardif.Abigale@epa.gov>, "Campbell, Ann" <Campbell.Ann@epa.gov>, "Shoaff, John" <Shoaff.John@epa.gov>, "Morgan, Ruthw" <morgan.ruthw@epa.gov>
Subject: RE: Phosphogypsum at 10 am today

<Fertilizer.Institute.SIGNED.pdf>

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 12/8/2020 10:16:28 PM
To: Idsal, Anne [idsal.anne@epa.gov]; Edwards, Jonathan [Edwards.Jonathan@epa.gov]
Subject: FW: Phosphogypsum in Government Road Construction
Attachments: FOIA EPA PG Roads Rule 12_8_20.pdf

Good evening Anne and Jon,

We've forwarded this FOIA request to the OAR FOIA large document review team. We have another FOIA on this subject with a similar request. It may be possible to work these together.
RPD will take the lead in responding and working with OAR IO staff.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Chandra Rosenthal <CRosenthal@peer.org>
Sent: Tuesday, December 08, 2020 3:35 PM
To: Idsal, Anne <idsal.anne@epa.gov>; Edwards, Jonathan <Edwards.Jonathan@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: Phosphogypsum in Government Road Construction

The attached was sent in this afternoon as FOIA Request EPA-2021-01324. PEER would like to understand the EPA process in evaluating the proposal of the Fertilizer Institute to use Phosphogypsum in public roads.

Chandra Rosenthal
Rocky Mountain Office Director
Public Employees for Environmental Responsibility
www.peer.org
(303) 898-0798

Message

From: Cherepy, Andrea [Cherepy.Andrea@epa.gov]
Sent: 7/20/2020 6:36:55 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Edwards, Jonathan [Edwards.Jonathan@epa.gov]
CC: Starrs, Charles [Starrs.Charles@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]
Subject: RE: Draft Briefing Materials
Attachments: TFI - Draft Terms and Conditions -7-20-2020.docx

Lee,

I have some minor edits to suggest to the first attachment. See above.

Andrea

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, July 20, 2020 12:30 PM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Cc: Starrs, Charles <Starrs.Charles@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; White, Rick <White.Rick@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>
Subject: Draft Briefing Materials

Jon and Andrea,

Attached are draft materials, two formats, for use tomorrow with Anne. One is a single page (albeit with narrow margins) that lists the conditions by category. The second is a crosswalk table of these same conditions with the regulatory reference and notes. I suspect we would want to use the former with Anne, but we should talk about that.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 7/20/2020 4:29:36 PM
To: Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]
CC: Starrs, Charles [Starrs.Charles@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]
Subject: Draft Briefing Materials
Attachments: TFI - Draft Terms and Conditions -7-20-2020.docx; TFI - Draft Terms and Conditions Table -7-20-2020.docx

Jon and Andrea,

Attached are draft materials, two formats, for use tomorrow with Anne. One is a single page (albeit with narrow margins) that lists the conditions by category. The second is a crosswalk table of these same conditions with the regulatory reference and notes. I suspect we would want to use the former with Anne, but we should talk about that.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 7/15/2020 3:05:48 PM
To: Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]
CC: White, Rick [White.Rick@epa.gov]; Holden, Patricia [Holden.Patricia@epa.gov]; Marbury, Candice [Marbury.Candice@epa.gov]; Robinson, Yvonne [robinson.yvonne@epa.gov]
Subject: Briefing materials
Attachments: TFI Briefing for AA 7-14-2020 lv.pptx

Hl Jon and Andrea,

Charles is on our call this morning, and he thought that we should move ahead with the brief for today.

Here is the slide deck. Patricia is ready to forward as appropriate, but I've also included Candice and Yvonne.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 12/3/2020 9:59:33 PM
To: Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]; White, Rick [White.Rick@epa.gov]
Subject: RE: AERMOD briefing

Jon,

Here's what I am thinking on TFI. I spoke to Charles Starrs at length this evening.

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Sent: Thursday, December 03, 2020 3:56 PM
To: Cherepy, Andrea <Cherepy.Andrea@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: AERMOD briefing

Ex. 5 Deliberative Process (DP)

From: Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Sent: Thursday, December 03, 2020 3:42 PM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: AERMOD briefing

Lee, Rick and Jon,

It looks like the AERMOD briefing for Anne got added to tomorrow morning's calendar, which is several days earlier than requested. Will you be ready tomorrow or do we need to work with Delaney to reschedule?

Andrea

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 8/21/2020 6:16:18 PM
To: Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]
Subject: TFI call
Attachments: Response to TFI-Draft Conditions Letter AA to TFI August 20.docx

Hi Jon and Andrea,

We finished the call with TFI and it went fine. No surprises. **Ex. 5 Deliberative Process (DP)**

Ex. 5 Deliberative Process (DP)

Here are the attendees:

TFI: Ed Thomas (who by the way once worked in the Office of Water), Corey Rosenbusch
Gallagher and Kennedy (represents TFI): Chris S. Leason
Mosaic: Deedra (Dee) Allen, Neil Beckingham, Lorine Card, Amita?
Lewis Brisbois (represents Mosaic): Karen Bennett
Nutrien: Eric Syrstad, Michael Williams
Simplot: Alan Prouty, Monty Johnson
EPA: me, Preston, Dan Schultheisz, Tom Peake

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

THE
FERTILIZER
INSTITUTE

December 1, 2020

Ms. Anne Idsal
Principal Deputy Assistant Administrator
U.S. Environmental Protection Agency
Office of Air and Radiation
1200 Pennsylvania Avenue, N.W.
Washington, DC 20460

Dear Ms. Idsal:

On October 14, 2020, The Fertilizer Institute (TFI) received the U.S. Environmental Protection Agency's (EPA or Agency) written approval, subject to certain conditions, of the use of Phosphogypsum (PG) in government road construction projects.[1] A notice of this approval was published in the *Federal Register* on October 20, 2020.[2] TFI appreciates the Agency's decision to approve PG use in road construction as an acceptable alternative to placement in stacks, consistent with Clean Air Act Regulations at 40 C.F.R. § 61.206.

The Agency's approval includes a list of "Initial" and "Other" conditions. EPA's "Initial" conditions refer to the information requirements set forth in the regulations at 40 C.F.R. § 61.206(b) that must be met prior to removing PG from a stack. EPA also determined that roads constructed with PG must be consistent with certain "Other" conditions, including a requirement that "[r]oads constructed with PG may not be abandoned (or otherwise permanently cease to be used as a road) and used for other non-road purposes or uses, including the construction of structures on such former roads."[3]

TFI seeks EPA's clarification of this condition, considering the following information from the administrative record.

1. **The administrative record supports the fact that road abandonment occurs very rarely and is subject to well-defined state and local requirements that are designed to ensure that such abandonment is done in a protective manner and subject to state and local review.**

[1] Letter from EPA Administrator, Andrew R. Wheeler, to Corey Rosenbusch, President and Chief Executive Officer, The Fertilizer Institute (Oct. 14, 2020) (EPA-HQ-OAR-2020-0442-0015) (hereinafter, "EPA Letter to TFI").
[2] 85 Fed. Reg. 66,550 (Oct. 20, 2020).
[3] *See* EPA Letter to TFI at 7.

- EPA's analysis[4] of public road abandonment found that decisions on abandonment are within state jurisdiction and demonstrate that local governments, state entities and the public can and do raise issues in road abandonment proceedings, resulting in limitations on the abandonment.

- Abandonment of government roads is subject to a petition process based on state statutes that include, among other things, public notice and comment and state agency approval.[5]

- Typically, abandonment is limited to a single right-of-way or easement and *structures or improvements are prohibited* in the former road area, except for stormwater, drainage and fencing structures approved by the local government.[6]

2. **In the extraordinary instance that an abandoned road would be repurposed and used for the construction of a house built using modern standards, the risk is 3 in 10,000 or less.**
   - EPA's review of the TFI/Arcadis Risk Assessment[7] acknowledges that "the TFI risk assessment does show that risk to a future resident of the site [*i.e.*, the residents of a house constructed on top of an abandoned road] might be acceptable depending upon the methods used to construct the house."[8]

   - The TFI/Arcadis Risk Assessment considered a road base that was 25 cm thick.[9] For the future resident scenario, TFI/Arcadis selected a 10 cm thick road base, adjusted due to site preparation and removal of the road cover layer (*i.e.*, the future home construction process is expected to result in mixing clean soil with PG).[10] However,

---

[4] *See* U.S. EPA Memorandum from Joseph Rustick, Staff Physical Scientist, Radiation Protection Division, Office of Radiation and Indoor Air, to Tom Peake, Director, Center for Waste Management Regulations (Oct. 15, 2020) (EPA-HQ-OAR-2020-0442-0004).
[5] *Id.* at 1, Att. A, Att. B.
[6] *Id.* at Att. B & C.
[7] U.S. EPA Office of Radiation and Indoor Air, *Review of the Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum Prepared for the Fertilizer Institute* (Oct. 14, 2020) (EPA-HQ-OAR-2020-0442-0018).
[8] *Id.* at 18.
[9] The 25 cm thickness of the road base is consistent with the assumed road base thickness in the TFI/Arcadis Risk Assessment submitted with the Petition. Arcadis Canada Inc., *Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum*, at 2-1 (Oct. 2019) (EPA-HQ-OAR-2020-0442-0007) (hereinafter, "TFI/Arcadis Risk Assessment"). This thickness was based on EPA's assumption in the 1992 document entitled "Potential Uses of Phosphogypsum and Associated Risks, Background Information Document" (EPA/520/1-91-029) (April 1992).
[10] The 10 cm thickness is an assumed value as described based on site preparation and road cover removal. This is consistent with the analysis provided in the TFI/Arcadis Risk Assessment submitted with the Petition. TFI/Arcadis Risk Assessment at 3-8.

assuming no further mixing of PG with clean soil, the TFI/Arcadis Risk Assessment shows that the risk would be in the acceptable 3 in 10,000 range using a road base thickness up to 25 cm.[11] Increasing the road base thickness up to 25 cm is not linear with the resulting dose and risk; that thickness would increase the indoor radon concentration by less than a factor of 2,[12] which for 26 years of residence would change the dose of about 46.8 mrem to about 75 mrem, still well below a lifetime reference level of 600 mrem corresponding to a risk of 3 in 10,000.[13] For comparison, the 600 mrem (*i.e.*, 3 in 10,000 risk) requires a Ra-226 concentration of 80 pCi/g (600 divided by 75 times 10 pCi/g). This Ra-226 concentration far exceeds the 35 pCi/g limit in the Petition and the average levels recently measured in U.S. PG stacks.[14]

- The Petition documents that the use of vapor barriers in construction is typical of modern construction practices.[15] However, even assuming no vapor barrier is used in construction, the lifetime dose would increase only to about 470 mrem, still well below the reference dose of 600 mrem corresponding to a risk of 3 in 10,000.[16]
- The existing record also demonstrates that other factors (*e.g.*, cracks in the slab foundation of the newly constructed house) do not significantly increase the risk.[17]

The points set forth above from the administrative record support EPA's conclusions that:

---

[11] The TFI/Arcadis Risk Assessment submitted with the Petition includes Figure 3.2, which shows the increased thickness of the road base would increase the radon flux and ultimately the risk to the reclaimer by less than a factor of 2 and would remain less than 3 in 10,000. *Id.* at 3-10.

[12] The actual modelled increase in indoor radon concentration is about a factor of 1.6, rounded to 2 for illustration. *Id.*

[13] Site preparation would include the addition of aggregate fill between the road base and the concrete slab. This somewhat porous layer would provide some, but not significant, radon mitigation. Consistent with TFI's approach of adopting conservative assumptions, TFI's radon calculation did not take into consideration any mitigation effect of the fill layer.

[14] TFI, *Supplement to The October 11, 2019 TFI Phosphogypsum Reuse Petition: 2019 Radium-226 Results for U.S. Phosphogypsum Stacks* (Dec. 5, 2019) (EPA-HQ-OAR-2020-0442-0011).

[15] As an example, the Florida building code requires vapor barriers to be installed below slab-on-grade floors. Florida Building Commission, Florida Building Code – Residential, Section R506.2.3, 6th Edition (2017).

[16] As described in the TFI/Arcadis Risk Assessment provided with the Petition, the vapor barrier reduces the radon flux by a factor or 10. Removing the vapor barrier affects the calculated result by increasing the radon and dose by a factor of 10. This factor was referenced in the Risk Assessment to: Kitto, M.E., & Perazzo, E., Experimental Determination of the Effectiveness of Radon Barriers (2010).

[17] The use of the diffusion coefficient value in the TFI/Arcadis model is comparable to that found from in-situ investigations and more accurately represents radon diffusion through a concrete slab than laboratory testing on cylinders and is considered reasonable for this purpose. *See* ANL, "Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil" (ANL/EAIS-8) Table 7.1 (1993).

1. Road abandonment and reuse are within the jurisdiction of the states and subject to well-established state and local requirements that are designed to ensure that abandonment is done in a protective manner and overseen by state and local review;
2. Redevelopment and construction on abandoned roads is unlikely; and
3. Any associated risk with a reclaimer scenario is low and can be safely managed through construction practices.

We respectfully request your concurrence with these conclusions. Your response will bring improved clarity and certainty to all stakeholders, including state agencies responsible for implementing the approved use of PG in road construction projects.

Sincerely,

Corey Rosenbusch
President and Chief Executive Officer

cc: Jonathan Edwards, Director, Office of Radiation and Indoor Air
Lee Veal, Director, Radiation Protection Division

Message

From: Emmerson, Caroline [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=AAFD8051883C48CDADD97E4C3F3C6307-AHEARN, CAROLYNE]
Sent: 9/14/2020 1:52:38 PM
To: Emmerson, Caroline [Emmerson.Caroline@epa.gov]
Subject: ORCR_OAR Discussion Paper_Use of Phosphogypsum in Road Construction 9 14 2020.docx
Attachments: ORCR_OAR Discussion Paper_Use of Phosphogypsum in Road Construction 9 14 2020.docx

Message

From: idsal.anne@epa.gov [idsal.anne@epa.gov]
Sent: 12/2/2020 2:02:38 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Edwards, Jonathan [Edwards.Jonathan@epa.gov]
CC: Cory, Preston [Cory.Preston@epa.gov]; Gustafson, Adam [Gustafson.Adam@epa.gov]
Subject: Fwd: Phosphogypsum Reuse Clarifications
Attachments: image001.png; image002.png; TFI_PG_Determination_Clarification_Request_12-1-20 final (002).pdf

Good morning,

Let's discuss this week or early next.

Best,
Anne

Sent from my iPad

Begin forwarded message:

> **From:** Ed Thomas <ethomas@tfi.org>
> **Date:** December 1, 2020 at 2:12:25 PM EST
> **To:** "Idsal, Anne" <idsal.anne@epa.gov>
> **Cc:** "Veal, Lee" <Veal.Lee@epa.gov>, edwards.jonathon@epa.gov, "Campbell, Ann" <Campbell.Ann@epa.gov>, "Leason, Chris S." <chris.leason@gknet.com>
> **Subject: Phosphogypsum Reuse Clarifications**
>
> Dear Ms. Idsal:
>
> The Fertilizer Institute would like to extend our sincere appreciation for the work you and your staff completed to evaluate and ultimately approve our petition to reuse phosphoogypsum as a road base material. As a follow up to the approval, we have attached a letter seeking EPA concurrence with several clarifications to certain "other" conditions within the letter. We look forward to your response, however, please feel free to contact me with any follow up questions you may have. I can be reached by email at ethomas@tfi.org or by mobile at 443-739-1358. Thanks in advance for your consideration regarding this matter.
>
> Sincerely,
> Ed Thomas
>
> **Ed Thomas**
> *Director, Regulatory Affairs*
> **TFI is moving! Effective December 11, our new address will be:**
> **The Fertilizer Institute**
> **4201 Wilson Boulevard**
> **Suite 700**
> **Arlington, Virginia 22203**
> Work: 202-515-2714
> Mobile: 443-739-1358
> E-mail: ethomas@tfi.org

Message

From: Shoaff, John [Shoaff.John@epa.gov]
Sent: 10/2/2020 4:10:47 PM
To: Idsal, Anne [idsal.anne@epa.gov]
CC: Cory, Preston [Cory.Preston@epa.gov]; Moor, Karl [Moor.Karl@epa.gov]; Harlow, David [harlow.david@epa.gov]; Dominguez, Alexander [dominguez.alexander@epa.gov]; Raymond, Kelley [Raymond.Kelley@epa.gov]; Tardif, Abigale (Abbie) [Tardif.Abigale@epa.gov]; Lubetsky, Jonathan [Lubetsky.Jonathan@epa.gov]; Campbell, Ann [Campbell.Ann@epa.gov]
Subject: FW: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)
Attachments: Action Memo TFI Petition Approval Austin to Wheeler Sept 21 2020.docx; CQR072.pdf; FR Typesetting TFI_.pdf; NESHAP Subpart R Approval TFI Request Other Use Phosphogypsum FRN_09212020.docx; TFI Approval Action Information Form 9-21-2020 .doc; TFI approval letter on AD Letterhead Sept 21 2020.docx; TFI_Approval_1-pager_9-21-2020 .docx; Transmittal memo Edwards to Austin TFI PG Request 9212020.docx; TFI response-Comms Plan_09 21 2020_ (002) rlso final.docx; RE: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)

Flag: Flag for follow up

Anne,

Attached for your review and signature is an action memo for the Phosphogypsum FRN en route to the Admin. to sign the action and accompanying letter. The review/concurrence email is also attached at the end and just to note that the Comms plan was updated from a desk statement to include a press release. Thanks.

John

JOHN SHOAFF | DIRECTOR
OFFICE OF AIR POLICY & PROGRAM SUPPORT (OAPPS)
OFFICE OF AIR & RADIATION | U.S. EPA | WJC NORTH 5442-C
1200 PENNSYLVANIA AVE. NW | MC 6103A | WASHINGTON, D.C. | 20460 | USA
Shoaff.john@epa.gov | **1-202-564-0531 DIRECT | 1-202-257-1755 MOBILE**

Message

From: Cory, Preston [Cory.Preston@epa.gov]
Sent: 10/2/2020 3:27:25 PM
To: Lubetsky, Jonathan [Lubetsky.Jonathan@epa.gov]; Moor, Karl [Moor.Karl@epa.gov]; Raymond, Kelley [Raymond.Kelley@epa.gov]; Dominguez, Alexander [dominguez.alexander@epa.gov]; Harlow, David [harlow.david@epa.gov]; Tardif, Abigale (Abbie) [Tardif.Abigale@epa.gov]
CC: Shoaff, John [Shoaff.John@epa.gov]; Campbell, Ann [Campbell.Ann@epa.gov]
Subject: RE: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)
Attachments: TFI response-Comms Plan_09 21 2020_ (002) rlso.docx

Jonathan,

I have reviewed the attached materials. Everything looks great, although I did make changes to the comms plan. My edits are attached.

Please let me know if anything else is needed from the IO to move this along.

Thanks,
Preston

From: Lubetsky, Jonathan <Lubetsky.Jonathan@epa.gov>
Sent: Thursday, October 1, 2020 2:40 PM
To: Moor, Karl <Moor.Karl@epa.gov>; Raymond, Kelley <Raymond.Kelley@epa.gov>; Dominguez, Alexander <dominguez.alexander@epa.gov>; Harlow, David <harlow.david@epa.gov>; Cory, Preston <Cory.Preston@epa.gov>; Tardif, Abigale (Abbie) <Tardif.Abigale@epa.gov>
Cc: Shoaff, John <Shoaff.John@epa.gov>; Campbell, Ann <Campbell.Ann@epa.gov>
Subject: FW: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)

This package is ready for your review. Please confirm who will take the lead on reviewing. Thanks!

From: Mcquilkin, Wendy <Mcquilkin.Wendy@epa.gov>
Sent: Thursday, October 01, 2020 2:34 PM
To: Shoaff, John <Shoaff.John@epa.gov>
Cc: ORIAREGPROCESSING <ORIAREGPROCESSING@epa.gov>; Campbell, Ann <Campbell.Ann@epa.gov>
Subject: Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute.(TFI)

TO: THE IMMEDIATE OFFICE FOR REVIEW AND CONCURRENCE FOR THE ADMINISTRATOR'S SIGNATURE.

Attached is the TFI Petition

RAY LEE
202 343-9463

Message

From: DeLuca, Isabel [DeLuca.Isabel@epa.gov]
Sent: 10/1/2020 4:30:59 PM
To: Ashley, Jackie [Ashley.Jackie@epa.gov]; Birgfeld, Erin [Birgfeld.Erin@epa.gov]; Block, Molly [block.molly@epa.gov]; Campbell, Ann [Campbell.Ann@epa.gov]; Clarke, Deirdre [clarke.deirdre@epa.gov]; Cortelyou-Lee, Jan [Cortelyou-Lee.Jan@epa.gov]; Cory, Preston [Cory.Preston@epa.gov]; Dominguez, Alexander [dominguez.alexander@epa.gov]; Drinkard, Andrea [Drinkard.Andrea@epa.gov]; Grantham, Nancy [Grantham.Nancy@epa.gov]; Haman, Patricia [Haman.Patricia@epa.gov]; Harlow, David [harlow.david@epa.gov]; Hewitt, James [hewitt.james@epa.gov]; Hubbard, Joseph [Hubbard.Joseph@epa.gov]; Idsal, Anne [idsal.anne@epa.gov]; Johnson, Taylor [Johnson.Taylor.C@epa.gov]; Jones, Enesta [Jones.Enesta@epa.gov]; Landeene, Sarah [Landeene.Sarah@epa.gov]; Linsk, Abigail (Abbey) [Linsk.Abbey@epa.gov]; Ludwig, Victoria [Ludwig.Victoria@epa.gov]; McFaul, Jessica [mcfaul.jessica@epa.gov]; Millett, John [Millett.John@epa.gov]; Moor, Karl [Moor.Karl@epa.gov]; Raymond, Kelley [Raymond.Kelley@epa.gov]; Richardson, RobinH [Richardson.RobinH@epa.gov]; Stevens, Katherine [stevens.katherine@epa.gov]; Tardif, Abigale (Abbie) [Tardif.Abigale@epa.gov]; Thundiyil, Karen [Thundiyil.Karen@epa.gov]; Walters, Ben [Walters.Ben@epa.gov]; Woods, Andrea [Woods.Andrea@epa.gov]
Subject: OAR Outlook for next couple of weeks.
Attachments: OAR Comms Outlook 10.01.20.docx

Hi all,
Attached is the OAR Comms Outlook for the next couple of weeks. Please let me or John know if you have any questions!

Thanks,
Isabel

Isabel DeLuca
Office of Air and Radiation, US EPA
(202) 343-9247

Message

From: Campbell, Ann [Campbell.Ann@epa.gov]
Sent: 9/10/2020 12:22:25 PM
To: Idsal, Anne [idsal.anne@epa.gov]; Moor, Karl [Moor.Karl@epa.gov]; Harlow, David [harlow.david@epa.gov]; Dominguez, Alexander [dominguez.alexander@epa.gov]; Cory, Preston [Cory.Preston@epa.gov]; Tardif, Abigale (Abbie) [Tardif.Abigale@epa.gov]; Shaw, Betsy [Shaw.Betsy@epa.gov]; Millett, John [Millett.John@epa.gov]; DeLuca, Isabel [DeLuca.Isabel@epa.gov]; Shoaff, John [Shoaff.John@epa.gov]; Rakosnik, Delaney [rakosnik.delaney@epa.gov]; Raymond, Kelley [Raymond.Kelley@epa.gov]; Kabanda, Thierry [Kabanda.Thierry@epa.gov]
Subject: FOR YOUR REVIEW: OAR Weekly Report

The report below is ready for your review. We are still checking on whether phosphogypsum will go out next week so there's a chance that will come off.

Hot Topics

Ex. 5 Deliberative Process (DP)

Upcoming Major Decisions and Events

Approval of the Request for Other Use of Phosphogypsum by The Fertilizer Institute

Ex. 5 Deliberative Process (DP)

Ann (Campbell) Ferrio
Chief of Staff
EPA/Office of Air and Radiation
Office: 202 566 1370

Message

From: Cory, Preston [Cory.Preston@epa.gov]
Sent: 8/31/2020 9:23:01 PM
To: Cook, Steven [cook.steven@epa.gov]
CC: Idsal, Anne [idsal.anne@epa.gov]
Subject: TFI Materials
Attachments: TFI FR_Notice_of_availability_Aug 26(inclusive fromDSchul-Aug252020-CStar-eds-Aug25).docx; Response to TFI-Letter PDAA to TFI 08242020ph.docx; TFI_briefing-pager_6-15-20_Final.docx; 062620 Fertilizer Institute.pdf; TFI - Draft Terms and Conditions -7-20-2020.docx

Steven,

Attached please find relevant materials pertaining to TFI's petition for alternative use of phosphogypsum:

1. TFI Petition Letter (June 2020) following up on Fall 2019 letter
2. TFI FR Notice
3. EPA Response Letter to TFI
4. Internal TFI briefing paper (in case you need more to read)
5. Internal TFI Draft Terms and Conditions

Thank you!
Preston

K. Preston Cory
Office of Air and Radiation
U.S. Environmental Protection Agency
Office: 202-564-0137
Cell: 202-924-2465
cory.preston@epa.gov

THE FERTILIZER INSTITUTE

June 26, 2020

Honorable Andrew Wheeler
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue Northwest
Washington, DC 20460

RE: Petition to Promote Reuse/Recycling of Phosphogypsum

Dear Administrator Wheeler:

We write to request your support for a petition, submitted to the U.S. Environmental Protection Agency (EPA) in the Fall of 2019 by The Fertilizer Institute (TFI), which would facilitate the recycling and reuse of phosphogypsum (PG), a by-product of the production of phosphate fertilizer. TFI represents the fertilizer industry. Our members provide plant nutrients that are responsible for nearly half the world's food supply. Additionally, the fertilizer industry supports nearly 500,000 American jobs and has an economic impact of more than $130 billion annually.

Phosphate is one of three nutrients critical to the growth of crops produced to feed the U.S. population and for export to feed millions around the world. The U.S produces over six million metric tons of phosphate fertilizer annually, making the U.S. the second largest global producer of this product.

Phosphogypsum is used beneficially for various purposes in many countries. However, in the U.S., which produces more than 46 million metric tons of PG annually, these uses are constrained by a 1992 agency rule. Under that rule, with only limited exceptions, phosphate fertilizer producers must place PG in engineered "stacks" adjacent to their fertilizer plants. These stacks are expensive to construct, maintain and close, consume enormous amounts of land that could be put to other productive use, are tall and readily visible, and increasingly have become the subject of public concern. Further, the rule results in significant additional costs on U.S. fertilizer producers, making them less competitive compared to foreign operations. Morocco is the world's leading producer of phosphate fertilizer—by far—and its state-owned company is not subject to comparable PG requirements.

The 1992 rule requires EPA approval for petitions seeking beneficial use of PG. TFI's petition requests that EPA authorize the use of PG as a road-base material or as an ingredient in

ED_005285_00002150-00001

Message

From: Campbell, Ann [Campbell.Ann@epa.gov]
Sent: 12/1/2020 4:05:12 PM
To: Moor, Karl [Moor.Karl@epa.gov]
CC: Idsal, Anne [idsal.anne@epa.gov]; Raymond, Kelley [Raymond.Kelley@epa.gov]; Shaw, Betsy [Shaw.Betsy@epa.gov]; Kabanda, Thierry [Kabanda.Thierry@epa.gov]; Rakosnik, Delaney [rakosnik.delaney@epa.gov]
Subject: RE: Transition Team Meeting Today
Attachments: EtO 2020 Transition Paper_10.15.20_final.docx; Heavy Duty Trucking & Aircraft Sectors 2020 Transition Paper_10.15.20_final.docx; IAQ and COVID 2020 Transition Paper_10.15.20_final.docx; NAAQS Implementation 2020 Transition Paper_10.15.20_final.docx; NAAQS Standard Setting 2020 Transition Paper_10.15.20_final.docx; OAR Presidential Transition Overview Paper 10-29-2020.docx; Ozone Transport 2020 Transition Pager_10.15.20_final.docx; Phosphogypsum 2020 Transition Paper_10.15.20_final.docx; RFS 2020 Transition Paper_10.15.20_final.docx; The Montreal Protocol and HFCs 2020 Transition Paper_10.15.20_final.docx; U.S. GHG Emissions Trends 2020 Transition Paper_10.15.20_final.docx; WIPP 2020 Transition Paper_10.15.20_final.docx; Affordable clean energy rule and clean power plan repeal litigation.docx; SAFE 1 rule (withdrawal of CA waiver for light duty GHG ZEV standards).docx; SAFE 2 rule (GHG light duty vehicle standards).docx; Selected legal hot topics and litigation cases.docx

Karl, the meeting has no been confirmed and is on your calendar for today at 2p. For ease of reference, I am attaching OAR's transition papers as well as OGC's papers. Please let me know if you have any questions or need anything additional.

Ann (Campbell) Ferrio
Chief of Staff
EPA/Office of Air and Radiation
Office: 202 566 1370

From: Campbell, Ann
Sent: Tuesday, December 1, 2020 9:35 AM
To: Karl Moor (Moor.Karl@epa.gov) <Moor.Karl@epa.gov>
Cc: Idsal, Anne <idsal.anne@epa.gov>; Raymond, Kelley <Raymond.Kelley@epa.gov>; Shaw, Betsy <Shaw.Betsy@epa.gov>; Kabanda, Thierry <Kabanda.Thierry@epa.gov>
Subject: FW: Transition Team Meeting Today

Karl, we are awaiting confirmation from the OA on OAR's first transition meeting today on vehicles and climate. It is tentatively scheduled for 2-3 with Sarah and Chris. Betsy and I both plan to join as well. Looks like Anne unfortunately has conflict but your schedule looks clear. Are you able to join us today?

Thank you,

Ann (Campbell) Ferrio
Chief of Staff
EPA/Office of Air and Radiation
Office: 202 566 1370

Message

From: Morgan, Ruthw [morgan.ruthw@epa.gov]
Sent: 10/16/2020 1:37:08 PM
Subject: Administrator's Weekly Report for the week ending October 16, 2020
Attachments: Administrator Weekly Report 101620.docx; Administrator Weekly Report 101620.pdf

Good morning Administrator Wheeler and colleagues,

Attached please find the **Administrator's Weekly Report** (in both PDF and Word), which includes programs and regional office updates for the week ending October 16, 2020.

Sincerely,
Ruth

Ruthw Morgan, Special Assistant
Office of the Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Ave., NW
Washington, DC 20460
(202) 564-1326
Morgan.Ruthw@epa.gov

Message

From: Campbell, Ann [Campbell.Ann@epa.gov]
Sent: 10/15/2020 9:46:28 PM
To: Idsal, Anne [idsal.anne@epa.gov]
CC: Shaw, Betsy [Shaw.Betsy@epa.gov]
Subject: Transition Papers
Attachments: NPM Template_OAR.docx; EtO 2020 Transition Paper_10.15.20_final.docx; Heavy Duty Trucking & Aircraft Sectors 2020 Transition Paper_10.15.20_final.docx; IAQ and COVID 2020 Transition Paper_10.15.20_final.docx; NAAQS Implementation 2020 Transition Paper_10.15.20_final.docx; NAAQS Standard Setting 2020 Transition Paper_10.15.20_final.docx; Ozone Transport 2020 Transition Pager_10.15.20_final.docx; Phosphogypsum 2020 Transition Paper_10.15.20_final.docx; RFS 2020 Transition Paper_10.15.20_final.docx; The Montreal Protocol and HFCs 2020 Transition Paper_10.15.20_final.docx; U.S. GHG Emissions Trends 2020 Transition Paper_10.15.20_final.docx; WIPP 2020 Transition Paper_10.15.20_final.docx

Anne, for your awareness, please find attached the 11 transition papers developed by the programs. These papers have undergone review by program leadership, Betsy, OGC, and myself. Also attached is an OAR overview, drafted in the template requested by the OA. The text largely draws upon the web and I suspect can be improved upon as needed.

The programs have been reviewing a number of other submissions from OGC, OITA, the regions and other offices from across the agency. They have done a wonderful job in this first round. All of our papers, along with the ones we've collected with OAR content are housed in a Teams site that we each have access to.

We are on track to meet our deadline to submit these papers to the OA tomorrow.

Thank you,

Ann (Campbell) Ferrio
Chief of Staff
EPA/Office of Air and Radiation
Office: 202 566 1370

Message

From: Cory, Preston [Cory.Preston@epa.gov]
Sent: 10/15/2020 3:28:07 PM
To: Idsal, Anne [idsal.anne@epa.gov]; Tardif, Abigale (Abbie) [Tardif.Abigale@epa.gov]
Subject: RE: EPA approves use of phosphogypsum in roads

Will do.

From: Idsal, Anne <idsal.anne@epa.gov>
Sent: Thursday, October 15, 2020 10:44 AM
To: Cory, Preston <Cory.Preston@epa.gov>; Tardif, Abigale (Abbie) <Tardif.Abigale@epa.gov>
Subject: Fwd: EPA approves use of phosphogypsum in roads

Please add to the phosphogypsum materials sent downstairs.

Sent from my iPad

Begin forwarded message:

> **From:** POLITICO Pro Agriculture <alert@email.politicopro.com>
> **Date:** October 14, 2020 at 7:25:28 PM EDT
> **To:** "Idsal, Anne" <idsal.anne@epa.gov>
> **Subject: EPA approves use of phosphogypsum in roads**
> **Reply-To:** "POLITICO, LLC" <reply-fe8e1c777760057a71-553241_HTML-954118245-1376319-140663@politicoemail.com>
>
> **EPA approves use of phosphogypsum in roads**
>
> By Bruce Ritchie
>
> 10/14/2020 07:24 PM EDT
>
> U. S. Environmental Protection Agency Administrator Andrew Wheeler on Wednesday approved an industry group's request to allow phosphogypsum, a byproduct of fertilizer production, to be used in building roadways.
>
> Wheeler granted a request from the Fertilizer Institute to use the waste, which contains radioactive material and is being stored in towering stacks at sites around Southwest Florida where fertilizer is produced from phosphate.
>
> Phosphogypsum contains radium, which decays to form radon, a cancer-causing, radioactive gas, the EPA said.
>
> **Details:** Studies from the Fertilizer Institute demonstrated that use of phosphogypsum in road construction is safe, avoids the risk of storing the material and represents the most significant effort towards finding an alternative use for the byproduct since the 1990s, EPA said in a news release. The agency said the group submitted the request a year ago.
>
> "Allowing the reuse of phosphogypsum shows EPA's commitment to working with industry in a way that both reduces environmental waste and protects public health," Wheeler said in the release Wednesday.

Reaction: Some Florida environmentalists were surprised by the announcement and are concerned that allowing phosphogypsum to be used in roads could present health risks from exposure to the material and groundwater contamination.

"Quite frankly this is something we have been preparing for for decades and hoping we would never have to address the issue on the federal level," Glenn Compton, chair of the ManaSota-88, a nonprofit environmental group, said in an interview. "It looks like it has presented itself."

Jaclyn Lopez, Florida director for the Center for Biological Diversity, listed previous studies the EPA had cited previously in determining that phosphogypsum was too radioactive for use in road projects.

"Without seeing the EPA's analysis (assuming there is one), I can't imagine what has changed, except the agency's tolerance for which and how many people get sick or die as a result of exposure," Lopez said in an email.

The prepared Federal Register notice said the agency will publish a docket in the case.

EPA spokesperson Enesta Jones said the agency needed time to respond to criticism and questions about the action announced Wednesday, including how the public could become involved at this point.

Kathy Mathers, vice president of public affairs for The Fertilizer Institute, did not respond to telephone messages and emails requesting comment.

What's next: Compton said he doesn't know what the next step is for ManaSota-88 and other environmental groups until they can review agency documents involving the announcement.

To view online:
https://subscriber.politicopro.com/agriculture/article/2020/10/epa-approves-use-of-phosphogypsum-in-roads-2009158

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This email was sent to idsal.anne@epa.gov by:
POLITICO, LLC
1000 Wilson Blvd.
Arlington, VA 22209
USA

Message

From: Idsal, Anne [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=B1BECA8121FB47A08E82B6BF2247A79B-IDSAL, ANNE]
Sent: 8/13/2020 1:40:40 PM
To: Campbell, Ann [Campbell.Ann@epa.gov]; Preston Cory (Katherine) (Cory.Preston@epa.gov) [Cory.Preston@epa.gov]
Subject: TFI response. sbh 07-23-2020 DH RLSO.docx
Attachments: TFI response. sbh 07-23-2020 DH RLSO.docx

Signed and ready to go. Thanks!

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

August 13, 2020

OFFICE OF
AIR AND RADIATION

Mr. Corey Rosenbusch
President and CEO
The Fertilizer Institute
425 Third Street, SW, Suite 950
Washington, D.C. 20024

Dear Mr. Rosenbusch:

Thank you for your letter to the Administrator dated June 26, 2020, regarding the petition submitted to the U.S. Environmental Protection Agency (EPA) by The Fertilizer Institute (TFI) concerning the use of phosphogypsum in road base and road pavement. The Administrator asked that I respond on his behalf.

We appreciate the discussions between EPA and the representatives of TFI and your member organizations on the content of the alternative use request for phosphogypsum. Those discussions have been collaborative and productive, resulting in an updated petition and risk assessment in April. EPA staff are grateful for the active cooperation of TFI's representatives that yielded this updated and improved request. At present, senior managers are continuing the technical and legal analysis necessary to provide a response, which we hope to provide in the near future.

Again, thank you for your letter and for your industry's continued commitment and essential contribution to the nation's food supply. I appreciate the opportunity to be of service and trust the information provided is helpful. If your staff have further questions, please reach out to Lee Ann B. Veal, Director of the Radiation Protection Division at [HYPERLINK "mailto:veal.lee@epa.gov"] or (202) 343-9448.

Sincerely,

Anne L. Austin
Principal Deputy Assistant Administrator

cc: James C. 'Joc' O'Rourke
President and CEO, The Mosaic Company

Chuck Magro
President and CEO, Nutrien, Inc.

Garrett Lofto

President and CEO, J. R. Simplot Company

Message

From: Idsal, Anne [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=B1BECA8121FB47A08E82B6BF2247A79B-IDSAL, ANNE]
Sent: 10/15/2020 12:10:11 PM
To: Campbell, Ann [Campbell.Ann@epa.gov]
CC: Moor, Karl [Moor.Karl@epa.gov]; Raymond, Kelley [Raymond.Kelley@epa.gov]; Dominguez, Alexander [dominguez.alexander@epa.gov]; Harlow, David [harlow.david@epa.gov]; Cory, Preston [Cory.Preston@epa.gov]; Tardif, Abigale (Abbie) [Tardif.Abigale@epa.gov]; Landeene, Sarah [Landeene.Sarah@epa.gov]; Shaw, Betsy [Shaw.Betsy@epa.gov]; Shoaff, John [Shoaff.John@epa.gov]; Millett, John [Millett.John@epa.gov]; DeLuca, Isabel [DeLuca.Isabel@epa.gov]; Rakosnik, Delaney [rakosnik.delaney@epa.gov]; Lubetsky, Jonathan [Lubetsky.Jonathan@epa.gov]; Kabanda, Thierry [Kabanda.Thierry@epa.gov]
Subject: Re: FOR YOUR REVIEW: OAR Weekly Report

Looks good. Thanks Ann!

Anne L. (Idsal) Austin
Principal Deputy Assistant Administrator - Office of Air and Radiation
U.S. EPA

On Oct 15, 2020, at 7:58 AM, Campbell, Ann <Campbell.Ann@epa.gov> wrote:

Good morning, please find below this week's report. Lots of moving pieces so please let me know if I missed anything.

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Ann (Campbell) Ferrio
Chief of Staff
EPA/Office of Air and Radiation
Office: 202 566 1370

Message

From: Idsal, Anne [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=B1BECA8121FB47A08E82B6BF2247A79B-IDSAL, ANNE]
Sent: 10/8/2020 3:17:23 PM
To: Campbell, Ann [Campbell.Ann@epa.gov]; Moor, Karl [Moor.Karl@epa.gov]; Raymond, Kelley [Raymond.Kelley@epa.gov]; Dominguez, Alexander [dominguez.alexander@epa.gov]; Harlow, David [harlow.david@epa.gov]; Cory, Preston [Cory.Preston@epa.gov]; Tardif, Abigale (Abbie) [Tardif.Abigale@epa.gov]; Landeene, Sarah [Landeene.Sarah@epa.gov]; Shaw, Betsy [Shaw.Betsy@epa.gov]; Millett, John [Millett.John@epa.gov]; DeLuca, Isabel [DeLuca.Isabel@epa.gov]; Shoaff, John [Shoaff.John@epa.gov]; Kabanda, Thierry [Kabanda.Thierry@epa.gov]; Rakosnik, Delaney [rakosnik.delaney@epa.gov]
Subject: RE: FOR YOUR REVIEW: OAR Weekly Report

Looks good. Thanks Ann!

From: Campbell, Ann <Campbell.Ann@epa.gov>
Sent: Thursday, October 8, 2020 8:04 AM
To: Idsal, Anne <idsal.anne@epa.gov>; Moor, Karl <Moor.Karl@epa.gov>; Raymond, Kelley <Raymond.Kelley@epa.gov>; Dominguez, Alexander <dominguez.alexander@epa.gov>; Harlow, David <harlow.david@epa.gov>; Cory, Preston <Cory.Preston@epa.gov>; Tardif, Abigale (Abbie) <Tardif.Abigale@epa.gov>; Landeene, Sarah <Landeene.Sarah@epa.gov>; Shaw, Betsy <Shaw.Betsy@epa.gov>; Millett, John <Millett.John@epa.gov>; DeLuca, Isabel <DeLuca.Isabel@epa.gov>; Shoaff, John <Shoaff.John@epa.gov>; Kabanda, Thierry <Kabanda.Thierry@epa.gov>; Rakosnik, Delaney <rakosnik.delaney@epa.gov>
Subject: FOR YOUR REVIEW: OAR Weekly Report

Please find this week's report below for your review. I think it's pretty straight forward. Please let me know if I should include E15 in the packages for signature. Thanks!

Hot Topics

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Ann (Campbell) Ferrio
Chief of Staff
EPA/Office of Air and Radiation
Office: 202 566 1370

Message

From: Idsal, Anne [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=B1BECA8121FB47A08E82B6BF2247A79B-IDSAL, ANNE]
Sent: 10/4/2020 9:59:15 PM
To: Campbell, Ann [Campbell.Ann@epa.gov]; Shoaff, John [Shoaff.John@epa.gov]
CC: Preston Cory (Katherine) (Cory.Preston@epa.gov) [Cory.Preston@epa.gov]
Subject: Action Memo TFI Petition Approval Austin to Wheeler Sept 21 2020.docx
Attachments: Action Memo TFI Petition Approval Austin to Wheeler Sept 21 2020.docx

Phosphogypsum is ready to go. Thanks!

Appointment

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 3/24/2020 8:44:54 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
CC: Rustick, Joseph [rustick.joseph@epa.gov]

Subject: NESHAP priorities
Attachments: NESHAP_priorities_4-2020.docx
Location: Skype Meeting

Start: 3/27/2020 1:00:00 PM
End: 3/27/2020 2:00:00 PM
Show Time As: Busy

Discuss program priorities and further development of the attached document

Join Skype Meeting

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Toll number: Ex. 6 Personal Privacy (PP) # (Dial-in Number) English (United States)

Find a local number

Conference ID: Ex. 6 Personal Privacy (PP)

Forgot your dial-in PIN? | Help

Appointment

From: Edwards, Jonathan [Edwards.Jonathan@epa.gov]
Sent: 12/10/2019 4:17:12 PM
To: Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Marbury, Candice [Marbury.Candice@epa.gov]; Holden, Patricia [Holden.Patricia@epa.gov]
CC: Mosser, Jennifer [Mosser.Jennifer@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]

Subject: Phosphogypsum Industry Petition for Alternative Use
Attachments: TFI 1-pager_OAR_12-2019 final.docx
Location: DCRoomWest1317

Start: 12/17/2019 9:00:00 PM
End: 12/17/2019 10:00:00 PM
Show Time As: Busy

Call In: Ex. 6 Personal Privacy (PP) Conference ID: Ex. 6 Personal Privacy (PP)

SPC: Yvonne Robinson Ex. 6 Personal Privacy (PP)

Technical Point of Contact: Lee Veal

Appointment

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 10/11/2019 7:43:21 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Major, Jonathan [Major.Jonathan@epa.gov]; Tong, Xinyue [Tong.Xinyue@epa.gov]
CC: OAR-ORIA-RPD-CWMR [OARORIARPDCWMR@epa.gov]; Rosencrantz, Ingrid [Rosencrantz.Ingrid@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]

Subject: NESHAP overview
Attachments: Phosphogypsum_10-16-2018_with_extra_slides.pptx
Location: DCRoomWest1424/ORIA

Start: 10/18/2019 6:00:00 PM
End: 10/18/2019 7:00:00 PM
Show Time As: Tentative

I'll be doing an overview of the radiation NESHAP program with our new staff.

Anyone from CWMR (or RPD) is welcome to attend; please note that we'll be working off the same slides used at the 2018 regional training workshop.

Appointment

From: Edwards, Jonathan [Edwards.Jonathan@epa.gov]
Sent: 8/14/2019 2:23:31 PM
To: Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
CC: Diaz, Charlene [diaz.charlene@epa.gov]; Holden, Patricia [Holden.Patricia@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Boyd, Mike [Boyd.Mike@epa.gov]

Subject: TFI Follow-up Briefing
Attachments: Phosphogypsum_TFI_8-14-2019_final.pptx
Location: DCRoomWest1317

Start: 8/14/2019 8:00:00 PM
End: 8/14/2019 9:00:00 PM
Show Time As: Tentative

Call-in information: **Ex. 6 Personal Privacy (PP)**

POC: Candice Marbury 202-343-9861

Appointment

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 12/3/2020 1:24:16 PM
To: Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]
CC: Diaz, Charlene [diaz.charlene@epa.gov]

Subject: Informal Discussion of TFI Clarification Memo
Attachments: TFI_PG_Determination_Clarification_Request_12-1-20 final (002).pdf
Location: Microsoft Teams Meeting

Start: 12/7/2020 4:00:00 PM
End: 12/7/2020 4:30:00 PM
Show Time As: Busy

Microsoft Teams meeting

Join on your computer or mobile app
Click here to join the meeting

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Ex. 6 Personal Privacy (PP) United States, Washington DC
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Appointment

From: Edwards, Jonathan [Edwards.Jonathan@epa.gov]
Sent: 6/17/2020 7:45:29 PM
To: Edwards, Jonathan [Edwards.Jonathan@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
CC: Diaz, Charlene [diaz.charlene@epa.gov]; Marbury, Candice [Marbury.Candice@epa.gov]; Holden, Patricia [Holden.Patricia@epa.gov]

Subject: The Fertilizer Institute request for alternative use of phosphogypsum
Attachments: TFI Briefing for ORIA Director final 7-6-2020.pptx
Location: Teams Meeting

Start: 7/7/2020 3:00:00 PM
End: 7/7/2020 4:00:00 PM
Show Time As: Busy

Purpose: To brief Jon on the Fertilizer Institute Request

Technical Point of Contact: Lee Veal

Scheduling Point of Contact: Yvonne Robinson

Schedulers to cc: Holden, Patricia

Join Microsoft Teams Meeting

Ex. 6 Personal Privacy (PP) United States, Washington DC (Toll)

Conference ID: Ex. 6 Personal Privacy (PP)

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Message

From: Stuenkel, David (Guest)
Sent: 7/15/2020 3:40:44 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]; Wieder, Jessica [Wieder.Jessica@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]

Ex. 5 Deliberative Process (DP)

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 9/30/2020 3:51:49 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; White, Rick [White.Rick@epa.gov]
Subject: RE: WIPP and Phosphogypsum transition papers
Attachments: Transition Paper WIPP 09302020.docx

Hi,
I made some edits. Let me know if these are problematic.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Friday, September 25, 2020 8:30 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: WIPP and Phosphogypsum transition papers

Lee,
I have revamped the WIPP transition paper to address your comments.
See what you think.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Thursday, September 24, 2020 4:04 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: WIPP and Phosphogypsum transition papers

Here is the revised TFI paper, with your comments addressed.

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Tuesday, September 22, 2020 4:11 PM
To: Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>

Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: WIPP and Phosphogypsum transition papers

Hi Tom, Dan,

Ex. 5 Deliberative Process (DP)

The PG paper looks good, with just a few edits due to the publicly available info piece and one sentence structure.

Thank you both.

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Tuesday, September 22, 2020 2:52 PM
To: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: WIPP and Phosphogypsum transition papers

All,
The WIPP and PG transition papers are attached for your review and editing pleasure.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 9/30/2020 12:55:17 PM
To: Peake, Tom [Peake.Tom@epa.gov]
Subject: RE: Do you have access to the phosphogypsum Teams/sharepoint files?

Hi Tom,

I'll check on it and let you know at management meeting.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, September 30, 2020 8:54 AM
To: Veal, Lee <Veal.Lee@epa.gov>
Subject: Do you have access to the phosphogypsum Teams/sharepoint files?

Lee,
Do you have access to our phosphogypsum documents in Teams? You don't need to be in the VPN to access the sharepoint files if you use Teams. It is the RadNeshaps Subpart R group, not the TFI Risk Assessment Review group as you may expect. I can't tell who has access.
The technical review document and the road abandonment document appear to be done though there is one edit up for debate on the technical review document.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 9/14/2020 7:52:56 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]
CC: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: RE: ORCR_OAR Discussion Paper_Use of Phosphogypsum in Road Construction 9 14 2020 330 pm.docx

Ex. 5 Deliberative Process (DP)

From: Emmerson, Caroline <Emmerson.Caroline@epa.gov>
Sent: Monday, September 14, 2020 3:41 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Coleman, Cheryl <Coleman.Cheryl@epa.gov>; Villamizar, Nicole <Villamizar.Nicole@epa.gov>; Chow, Rita <Chow.Rita@epa.gov>
Subject: FW: ORCR_OAR Discussion Paper_Use of Phosphogypsum in Road Construction 9 14 2020 330 pm.docx

Lee,

Attached are the agenda for tomorrow's meeting, ORCR's Discussion Paper, and ORCR's suggested edits to the Draft TFI Approval letter. We look forward to talking with you tomorrow.

Thanks,

Caroline

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 9/21/2020 6:25:12 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
CC: White, Rick [White.Rick@epa.gov]
Subject: FW: 09232020: Briefing Materials for Fertilizer Institute Phosphogypsum meeting
Attachments: TFI Administrator Briefing Materials for 9232020.docx; TFI approval letter on AD Letterhead Sept 18 .docx

Hi Tom and Dan,

I'm still trying to square away getting you both on the call with the Administrator officially. Here is the call in and it is at 4:30pm - 5:00 pm on Wednesday. Ex. 6 Personal Privacy (PP) dial-in: Ex. 6 Personal Privacy (PP)

The attached documents were sent today from Ann Campbell Ferrio to the OA. I spoke with Jon this afternoon about the brief. After opening remarks from Anne/Jon, I will plan to start the brief. We've only done one other brief in RPD, but Jon has a little more experience. He recommends going through the briefing materials, augmenting with language from the Action memo and approval perhaps, and keeping it somewhat direct.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
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www.epa.gov/radiation

From: Campbell, Ann <Campbell.Ann@epa.gov>
Sent: Monday, September 21, 2020 1:02 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Edwards, Jonathan <Edwards.Jonathan@epa.gov>; OAR Briefings <OAR_Briefings@epa.gov>
Subject: FW: 09232020: Briefing Materials for Fertilizer Institute Phosphogypsum meeting

Ann (Campbell) Ferrio
Chief of Staff
EPA/Office of Air and Radiation
Office: 202 566 1370

From: Campbell, Ann
Sent: Monday, September 21, 2020 1:01 PM
To: Hyman, Alana <Hyman.Alana@epa.gov>; Scott, Corey <scott.corey@epa.gov>; Vella, Sophia <Vella.Sophia@epa.gov>
Cc: Preston Cory (Katherine) (Cory.Preston@epa.gov) <Cory.Preston@epa.gov>
Subject: 09232020: Briefing Materials for Fertilizer Institute Phosphogypsum meeting

Please find attached the briefing materials for Wednesday's meeting on the Fertilizer Institute's request on Phosphogypsum.

Ann (Campbell) Ferrio
Chief of Staff
EPA/Office of Air and Radiation
Office: 202 566 1370

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 9/29/2020 7:19:05 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: technical summary

Ex. 5 Deliberative Process (DP)

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Tuesday, September 29, 2020 3:08 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: technical summary

Ex. 5 Deliberative Process (DP)

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Tuesday, September 29, 2020 2:24 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: technical summary

Jon et al,
I did a quick read through again. I made a couple of very minor edits like adding in (BID) and deleting a space or adding/deleting a word in a couple of places. I have one comment on the yellow that I have in the document that I think should be addressed before we give it to Lee.
Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Tuesday, September 29, 2020 1:00 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: technical summary

Clean copy for Lee is here: Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Did you want to glance over it again before sending it up?

Message

From: Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]
Sent: 9/21/2020 2:50:10 PM
To: Peake, Tom [Peake.Tom@epa.gov]
Subject: RE: Good morning and anything for the 10 am management meeting?
Attachments: Geochemistry Briefing for Lee.pptx

This is the latest version. The presentation itself falls in at around 25 minutes.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Monday, September 21, 2020 10:46 AM
To: Santillan, Eugenio-Felipe <santillan.eugenio-felipe@epa.gov>
Subject: RE: Good morning and anything for the 10 am management meeting?

Jay,
Can you send me the latest one? I skimmed through what Ingrid had commented on and I concur that it was looking pretty good so I won't have many comments, I'm sure.

Have you done a time check on it? I don't think we have but 30 minutes.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
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cell phone: 202-465-5904

From: Santillan, Eugenio-Felipe <santillan.eugenio-felipe@epa.gov>
Sent: Monday, September 21, 2020 8:53 AM
To: Peake, Tom <Peake.Tom@epa.gov>
Subject: RE: Good morning and anything for the 10 am management meeting?

Let me know if you have any comments on the geochemistry briefing. I'll probably have to send it to Patricia at the end of the day.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Monday, September 21, 2020 8:19 AM
To: OAR-ORIA-RPD-CWMR <OARORIARPDCWMR@epa.gov>
Subject: RE: Good morning and anything for the 10 am management meeting?

We also have the GAO WIPP report to review.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Monday, September 21, 2020 8:18 AM
To: OAR-ORIA-RPD-CWMR <OARORIARPDCWMR@epa.gov>
Subject: Good morning and anything for the 10 am management meeting?

Happy, chilly Monday!
I hope you were able to enjoy the weather this weekend.

For the management meeting I have to report:

Ex. 5 Deliberative Process (DP)

TFI documents needed immediately are in the ORIA IO for review. The technical review document and the road abandonment document are being finalized over the next couple of days.
Ingrid is out this week.
Our WIPP overview meeting this morning will be rescheduled. Tuesday we have the borehole plugging and geochemistry briefings for Lee.

What else should we report?

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 9/14/2020 6:15:26 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Lee, Raymond [Lee.Raymond@epa.gov]
CC: Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]
Subject: TFI files
Attachments: CQR072.pdf; FR Typesetting TFI_.pdf; Response to TFI- Letter PDAA to TFI 09102020 FINAL DRAFT .docx; TFI Approval Action Information Form 9-14-2020 FINAL.doc; TFI FR_Notice_of_availability_Aug 27 FINAL DRAFT (needs cites).docx; TFI Press Release_9-11.docx; TFI_Approval_1-pager_9-14-2020 FINAL DRAFT ADMIN.docx; Action Memo TFI Petition Approval Austin to Wheeler Sept 14 2020 FINAL DRAFT.docx; TFI Communications Plan_9-11-20.docx

Hi Dan and Ray,

This is the last copy of the FR notice that I have related to the TFI project, along with all the files that I have that are in final. I'd like to confirm with you a few items and ask for any other changes/corrections:

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
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Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 9/21/2020 2:44:41 PM
To: Peake, Tom [Peake.Tom@epa.gov]
Subject: RE: Transition Briefing Papers - due 9/28

Yes.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Monday, September 21, 2020 10:43 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: FW: Transition Briefing Papers - due 9/28
Importance: High

I will get the WIPP one. Can you do the TFI one?

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Tuesday, September 15, 2020 2:08 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Yale, Kenneth <yale.kenneth@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Snead, Kathryn <Snead.Kathryn@epa.gov>; White, Rick <White.Rick@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Subject: Transition Briefing Papers - due 9/28
Importance: High

Hi Jess, Tom and Ken,

As I mentioned last week, the EPA 2020 Presidential Transition coordination is currently underway. Andrea Cherepy is the lead for ORIA, Ann (Campbell) Ferrio is the lead for OAR, and the Agency level effort will be led by Wes Carpenter, Acting Deputy Chief of Staff in the Administrator's Office.

Under the auspices of the Presidential Transition Act of 1963 and subsequent statutory updates, including the Presidential Transition Enhancement Act of 2019, EPA has major requirements to complete, including the National Program Managers (NPMs) creating and/or updating briefing materials.

Rick and I were able to speak with Jon and Andrea about the RPD submission, and we have these three topics that we feel would be worthy of one pagers for the transition team:

1. WIPP Expansion
2. ORIA ER Responsibilities (includes radiation risk comms, overall preparedness, key exercises in 2021 1Q)
3. Phosphogypsum/TFI

Remember that all information in transition materials must be **publicly available information**. We should use this as an opportunity to showcase our important work and highlight challenges that may be informative to any potential new political leadership.

Here are OAR's briefing paper topics from the 2016 transition:

- Biomass
- Clean Power Plan
- Climate Change & the Transportation Sector
- NAAQS Implementation

- Renewable Fuel Standards
- The Montreal Protocol & HFCs
- The Paris Agreement on Climate Change
- U.S. GHG Emission Trends

As of right now, we are being told to use the 2016 format (see attached examples – Biomass and CPP) for the 2020 transition materials. That could change, however, if OMB, GSA, and OPM requires changes. The Office of the Administrator expects to receive supplemental guidance shortly, so I appreciate your flexibility. While we haven't been given an internal OAR deadline just yet for draft briefing papers, final briefing materials are due to our agency transition team by Friday, October 16. Therefore, we shoot **aim to have our papers complete by September 30th**. As a way of translation for internal RPD review/edit Sept 28. Andrea will let us know if OAR needs them sooner.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
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www.epa.gov/radiation

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 8/24/2020 2:00:43 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; White, Rick [White.Rick@epa.gov]
CC: Lee, Raymond [Lee.Raymond@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: RE: Revised Draft FR Notice for TFI

Ex. 5 Deliberative Process (DP)

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, August 24, 2020 9:58 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

Let's first chat with Charles. We may be restricted to answering the request that we have.

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, August 24, 2020 9:53 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

And no, this has not been discussed with Charles, as far as I know. It just occurred to me (perhaps it had already occurred to others).

From: Schultheisz, Daniel
Sent: Monday, August 24, 2020 9:41 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

Ex. 5 Deliberative Process (DP)

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, August 24, 2020 9:36 AM
To: Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>

Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

Hi Tom and Dan,

I added in Ray Lee and Jon Walsh for completeness.

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Monday, August 24, 2020 9:26 AM
To: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

I just looked at it and deleted a couple of comments since Dan addressed them.

I think Dan did a terrific job adding in relevant background and focusing the discussion.

I think we can review this in parallel.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, August 24, 2020 9:16 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>

Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: Revised Draft FR Notice for TFI

You can edit this and also access it through Teams without being in the VPN. Should it also go to the rest of the team at this point? You will see a question for Joe and Stefanie, which I will also send them separately.

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 7/10/2020 12:46:48 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
CC: Rustick, Joseph [rustick.joseph@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]
Subject: draft AA briefing
Attachments: TFI Briefing for AA 7-8-2020_modified.pptx; TFI Briefing for AA 7-8-2020.pptx

This took me a good deal longer than I had hoped, so I'm sending to everyone. I saved a "modified" version when I

Ex. 5 Deliberative Process (DP)

Jon

Message

From: Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]
Sent: 9/14/2020 11:19:37 AM
To: Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]
Subject: RE: Mostary reference
Attachments: mostary_s.pdf

Attached.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Friday, September 11, 2020 1:28 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Santillan, Eugenio-Felipe <santillan.eugenio-felipe@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>
Subject: Mostary reference

Anybody have this reference:
Mostary, S. 2011. Trace metals leachability characterization of phosphogypsum. Masters Thesis. Engineering, University of Florida, Gainesville, FL. 141 pp.

This was listed in the Comms plan. Can somebody point me to this reference or send it to me?

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

TRACE METALS LEACHABILITY CHARACTERIZATION OF PHOSPHOGYPSUM

By

SHABNAM MOSTARY

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING

UNIVERSITY OF FLORIDA

2011

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To my Parents for all their love and support

ED_005285_00002627-00003

ACKNOWLEDGMENTS

I would like to thank my committee chairman, Dr. Timothy G. Townsend for his patience and encouragement throughout my graduate program. I also wish to thank the remaining members of my committee, Dr. Paul A. Chadik and Dr. Ben Koopman for their insight and review of this thesis.

I would also like to thank my fellow graduate students in Solid and Hazardous Waste, for their assistance and support with this study.

Final thanks are extended to Mosaic Fertilizer, LLC, for supporting this research. Special thanks go to Elizabeth Foeller (Research & Development Manager) and Charlotte Brittain (Engineering Superintendent Environmental Solutions). Also I want to thank the Solid Waste Management Division in Polk County, Florida for their help.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
CFS	Cancer Slope Factors
DI Water	Deionized Water
EPA	Environmental Protection Agency
EPTOX	Extraction Procedure Toxicity
EW	East Wall
FIPR	Florida Institute of Phosphate Research
GWCTL	Groundwater Cleanup Target Level
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrophotometer
L/S Ratio	Liquid to Solid Ratio
LOAEL	Lowest Observed Adverse Effect Level
MEP	Multiple Extraction Procedure
MSW	Municipal Solid Waste
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NOAEL	No Observed Adverse Effect Level
PG	Phosphogypsum
RCRA	Resource Conservation and Recovery Act
RFD	reference dose
SPLP	Synthetic Precipitation Leaching Procedure
SW	South Wall
TCLP	Toxicity Characteristic Leaching Procedure
TDS	Total Dissolved Solids
UCL95	95% Upper Confidence Limit
USGS	United States Geological Survey

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WW	West Wall

Abstract of Thesis Presented to the Graduate School
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TRACE METALS LEACHABILITY CHARACTERIZATION OF PHOSPHOGYPSUM

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Phosphogypsum (PG), a primary byproduct from phosphoric acid production, is accumulated in large stockpiles and occupies vast areas of land. The aim of this study was to characterize the trace metals leachability of phosphogypsum under different environmental conditions. For this purpose multiple batch leaching tests were conducted to observe the leaching behavior of PG elements. Based on the toxicity characteristic leaching procedure (TCLP) and extraction procedure toxicity (EPTOX) test, none of the metals (Ag, As, Ba, Cd, Cr, Pb, Se) exceeded the regulatory toxicity limits; thus PG samples tested did not meet the definition of EP Toxicity under the Resource Conservation and Recovery Act (RCRA). It is notable that mercury was not tested in this study. Results from the TCLP, synthetic precipitation leaching procedure (SPLP) and deionized water (DI) extraction, leached relatively similar concentrations of inorganic constituents (except calcium). Aluminum and iron concentrations exceeded their respective groundwater cleanup target level (GWCTL) in SPLP leachates. In the multiple extraction procedure (MEP), most of the metals leached at greater concentration in the second extraction than in the first. In a leaching test utilizing municipal solid waste (MSW) leachate as the extraction fluid, a few constituents of PG

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such as calcium and sulfate considerably leached out. Calcium leached more in the MSW leaching test than TCLP and SPLP. Aside from calcium and strontium there was no significant leaching of other metals in the MSW leaching test. Though concentration of arsenic (UCL_{95}) was above GWCTL in total metal analysis, it was not detected in any of the leaching test.

CHAPTER 1
INTRODUCTION

1.1 Phosphogypsum and Its Management

Phosphogypsum (PG), a waste by-product from the wet manufacturing process of phosphoric acid, is abundant in Florida due to the presence of this industry. The composition of PG is variable and is related to the source of phosphate rock as well as the manufacturing process. Gypsum ($CaSO_4 . 2H_2O$) is the main component; however, PG also contains low concentrations of P and some of the impurities that were originally in the phosphate rock (F, trace elements and naturally occurring radionuclides). Some of the minor elements that are common, such as F, As, Cd, P, and S, have the potential to pose environmental health concern if excessive levels are transported into ground or surface waters. Thus, there are environmental concerns in regards to the potential movement of fluoride, sulfate, certain trace elements, and radionuclides from the phosphogypsum stacks into groundwater. PG is currently placed in large piles or "stacks" to prevent it from entering the environment. Leachate from these "gyp stacks", as they are called, must be properly understood to minimize the risk of environmental contamination.

Prior to 1989, PG was treated as any other item of commerce. The US Environmental Protection Agency (EPA) first issued the National Emissions Standards for Hazardous Air Pollutants (NESHAP) for phosphogypsum in 1989 (54 FR 51654, December 15, 1989). The 1989 rule required that all phosphogypsum be stored in stacks. EPA also prohibited all phosphogypsum research and uses, such as agricultural or indoor research and development.

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In response to several petitions, EPA conducted risk assessments and revised the standard to permit alternate uses of PG in 1992 (40 CFR Part 61, Subpart R). The 1992 revision permitted uses of PG for agricultural uses (as a conditioner for soils containing high quantities of salt or low quantities of calcium and other nutrients), research and development projects and other alternate uses that are approved by EPA on a case-by-case basis.

In 1999 EPA increased the amount of phosphogypsum which may be used in indoor laboratory research from 700 to 7,000 pounds per experiment, with no limit on the number of experiments (40CFR 61.205). Under the 1999 rule, PG may be lawfully removed from a stack and distributed in commerce for use in agriculture if the average radium-226 concentration of the PG does not exceed 10 picocuries per gram (pCi/g)(40CFR 61.204). The owner or operator of the stack from which the PG is removed shall determine annually the average radium-226 concentration at the location in the stack from which the PG will be removed. PG may not be lawfully removed from a stack and distributed or used for any purpose other than agriculture and research purposes without prior EPA approval (40CFR 61.204). This restriction on the maximum radium radioactivity essentially eliminates the use of southern/central Florida phosphogypsum because its radium-226 levels are commonly in the range of 20 to 35 pCi g^{-1} (Guidry 1990; May and Sweeney 1984a). The restriction does not impact phosphogypsum from northern Florida or North Carolina, which generally have lower levels of radium-226.

Considerable research has been conducted to evaluate the leachability of toxic metals (As, Ba, Cd, Cr, Hg, Pb, Se and Ag) from phosphogypsum by TCLP and

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EPTOX. Several researchers have conducted leaching tests to estimate mobility of trace metals, radionuclides and rare earth metals from PG using different leaching solutions like distilled water, aqua regia, salt water etc.

1.2 Objectives

The primary objective of this thesis was to determine typical trace metal leaching behavior of PG using standardized regulatory leaching tests for solid wastes. Leaching tests play an important role in the reuse of raw waste materials as secondary materials. Analyses such TCLP, SPLP, EPTOX, MEP that would typically be required for a beneficial use demonstration in Florida were conducted. These analyses were conducted to evaluate the leachability of trace metals (Ag, Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mn, Na, Ni, Pb, Sb, Se, Sn, Sr, V, Zn) in PG. Laboratory leaching tests which generate leachate from waste have been used to evaluate leachability of hazardous constituents (As, Ba, Cd, Cr, Pb, Se, Ag) from PG. The results (total and leachable concentrations of inorganic constituents) were compared to Florida's risk-based target levels like soil cleanup target level (SCTL) and groundwater cleanup target level (GWCTL). PG leachability using different solutions like MSW leachate and DI water was also examined. Knowledge on leaching behavior of PG could help to explore disposal options and assess the risk associated with beneficial-use options for PG.

This study investigates one particular phosphogypsum stack in an attempt to characterize PG leachability that would be typical for many of the other stacks in central Florida. Chapter 2 investigates the literature pertinent to PG production and leachate resulting from PG and leaching tests. Chapter 3 discusses the materials and methodology used in this research. Chapter 4 presents the results from various leaching tests. Finally, discussions of the results are presented in Chapter 5.

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CHAPTER 2
LITERATURE REVIEW

2.1 Phosphoric Acid Production

Phosphogypsum is the primary byproduct generated from the wet-acid process for producing phosphoric acid from phosphate rock. Phosphoric acid is an industrial raw material required for the production of phosphate fertilizer. Phosphate rock, mined in open pit mines, does not have a definite chemical composition and the composition varies in different mining areas. Phosphate ore contains roughly one-third quartz sands, one-third clay minerals, and one third phosphate particles (USEPA 1992). Impurities like calcium, fluoride, chlorides, chromium, rare earths and radio nuclides are also common. United States is the world's leading producer and consumer of phosphate rock and phosphate fertilizers (USGS 2002). Extensive deposits of phosphate rock are found in Florida, Tennessee, North Carolina and Idaho. As a result of the low aqueous solubility of calcium phosphate, the phosphate content of the rock is converted into phosphoric acid to produce fertilizer. Phosphate ore composition partly determines the nature of the phosphorus fertilizer and phosphogypsum. For every ton of phosphoric acid produced, 4.5-5.5 tons of phosphogypsum are produced (Saylak et al. 1988).

According to a mineral industry survey conducted by U.S. Geological Survey (USGS) in 2007, a total of twelve phosphate rock producing mines were active nationwide (Table 2-1). In Florida, phosphate rock is mined and processed by three companies: CF Industries, Inc., The Mosaic Co., and PCS Phosphate Co., Inc. (USGS 2007).

Phosphate rock is usually treated by a physical process called beneficiation; a process prior to acid treatment in order to concentrate the P content of the ore (Becker

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1989). Beneficiation often involves concentration by washing, screening and flotation. Phosphoric acid is produced either by dry thermal or wet acid methods. The dry thermal method produces elemental phosphorus using an electric arc furnace. Phosphoric acid produced by dry thermal process is of a much higher purity and is used in the manufacture of high grade chemicals, pharmaceuticals, detergents, food products, beverages, and other non fertilizer products.

In the wet acid process, phosphate rock is treated with concentrated sulfuric acid and water to produce gypsum ($CaSO_4.2H_2O$), phosphoric acid and hydrogen fluoride. Wet process phosphoric acid is used in fertilizer production because it is more economical. The following is a simplified chemical reaction to illustrate the process (Luther et al. 1992).

$$Ca_{10}(PO_4)_6F_2 + 10H_2SO_4 + 20H_2O \rightarrow 10CaSO_4.2H_20 + 6H_3PO_4 + 2HF$$

Once crystallized, the gypsum is separated from the acid by filtration, mixed with water and transferred as slurry to onsite disposal areas referred to as phosphogypsum stacks. The phosphogypsum stacks are an integral part of the overall wet process.

The phosphogypsum slurry is pumped to the top of the stack and discharged into perimeter deposition ponds. The process water is decanted into a center storage pond and then removed from the stack for recycle via a siphon. The phosphogypsum slurry begins to form a small pond on top of the stack with the growth of stack. Workers dredge gypsum from the pond to build up the dike around it and the pond gradually becomes a reservoir for storing and supplying process water. As the wet process requires large quantities of water, the water impounded on the stack is used as a reservoir that supplies and balances the water needs of the process.

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2.2 Potential Uses of Phosphogypsum

EPA first banned any use of phosphogypsum in 1989. Since then it has been a divisive issue on if and how to use phosphogypsum. As a local material, phosphogypsum stacks can be found extensively in Florida. However, due to the 1992 EPA ban on the use of phosphogypsum, research has slowed dramatically. As a result, special provisions must be made to FDEP and EPA before this material can be used other than agricultural purposes.

It is of interest to the fertilizer industry to find effective and economical long-term solutions for the management of PG; this would help to minimize space requirements and the potential for environmental impact caused by the accumulation of PG stacks.

Several research projects have investigated practical application of PG for a variety of purposes, including its use as road fill material (May 1983; Chang 1989; Lloyd 1985) and as a soil stabilizer (Degirmenci 2006). Several roads and parking lots were constructed using PG or cement-PG. They are used daily in Florida and Texas with no reported negative environmental impacts (Nifong and Harris 1993). Sulfur deficiencies exist in soils of the southeastern US. Phosphogypsum soil amendment is a possible solution to correct this deficiency because it provides a sulfur source that is slowly available to the plants and is not easily leached out of the soil by rainfall (Lloyd 2004).

Stanley and Lloyd (1992) studied phosphogypsum, reporting that PG is currently being wasted and that PG enriches the soil. Lloyd states that “PG has been proven to be a suitable amendment for many soil types and is an excellent fertilizer source of sulfur, calcium and phosphorous”. He argues that “Any soil that tends to surface-harden

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and resist water would benefit from PG. It creates a more porous texture that soaks up rainfall".

In the past, countries such as France and Japan used phosphogypsum for construction of roadways and landfills and as a building material for houses. Research has been conducted in France to use PG for embankment construction (Moussa et al. 1984). Their study showed that re-utilization of PG is possible in well-determined conditions of placement and use.

Studies suggest that PG along with coal fly ash can be used as an amendment to improve rice paddy soil fertility (Lee et al. 2009). It was concluded that the fly ash and PG mixture could be a good source of inorganic soil amendments to restore the soil nutrient balance in rice paddy soil.

Extensive research has been conducted to recover sulfur from PG. In general, sulfate is converted to sulfur dioxide by a high temperature decomposition of calcium sulfate in the PG. The sulfur dioxide is scrubbed from the gaseous emissions and sent to the facility's chemical plant where it is converted to sulfuric acid. This is then utilized in the wet acid process (US EPA 1992). This method is not economical if the price of sulfur is too low.

2.3 Leaching Tests in Solid Waste Management

Leaching is a method to remove soluble components from a solid matrix. Many leaching test procedures have been developed to simulate the leaching processes of wastes in landfills or other disposal scenarios; these assist in evaluating potential risks to human health and environment from solid wastes. Therefore, leaching tests are often used in the decision making process of solid waste management. Leaching tests are used to estimate the potential concentration of contaminant that leaches from a solid

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waste when exposed to water or similar extraction solution. In general, there are two types of leaching tests: batch leaching tests and dynamic column/lysimeter tests. Some common batch leaching tests include Extraction Procedure Toxicity (EPTOX), Toxicity Characteristic Leaching Procedure (TCLP), Synthetic Precipitation Leaching Procedure (SPLP), American Society for Testing and Materials (ASTM) extraction test and Multiple Extraction Procedure (MEP). While batch leaching tests are characterized by a constant liquid to solid ratio, dynamic leaching tests are characterized by increasing liquid to solid ratio as the experiment proceeds. Batch tests typically involve adding waste to an extraction solution and then agitating the mixture for a short period of time (typically less than 24 hour).Thus, batch tests offer a relatively rapid, cost effective method for the assessment of metal leachability. Batch tests are primarily conducted as a regulatory tool but they can also be conducted in a manner to examine a specific variable's influence on metal mobility, like impact of pH, liquid to solid ratio, etc.

2.3.1 Toxicity Characteristic Leaching Procedure (TCLP)

TCLP (EPA Method 1311) is the most frequently used batch test in the management of solid waste. The TCLP was designed by the US Environmental Protection Agency (EPA) to provide a relatively quick test to determine whether a solid waste should be characterized as hazardous and thus be managed in a more controlled manner. The TCLP attempts to mimic reducing, low pH environmental conditions in MSW landfills. The extraction fluid (pH 4.93 ± 0.05) simulates a scenario where a potentially hazardous waste is co-disposed with MSW. The primary extraction fluid is a buffered acetic acid solution in a liquid to solid ratio of 20:1 for 18 ± 2 hours. Particle size reduction is required if the particle is greater than 1 cm in its narrowest dimension. The concentrations of contaminants are compared to toxicity characteristic (TC) limit

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concentrations outlined in 40CFR261.3 to determine hazardous waste designation. The TC limits for the eight metals used in determination of hazardous waste are presented in Table 2-2. Note that there are a number of organic contaminants which also carry a toxicity characteristic limit. TCLP uses acetic acid (weak acid) which has a strong ability to complex or chelate metals.

2.3.2 Synthetic Precipitation Leaching Procedure (SPLP)

The SPLP is an EPA SW-846 analytical method (EPA Method-1312) designed to mimic the mobility of toxic contaminants when exposed to acidic rainfall. The SPLP is thus used to evaluate the potential for metal leaching into ground and surface waters from waste exposed to rainfall (Jang and Townsend 2001; Brantley and Townsend 1999). The time and liquid-to-solid ratio are the same as in the TCLP, but SPLP utilizes an extraction fluid intended to simulate precipitation or acid rain. Particle size reduction is required if the particle is greater than 1 cm in its narrowest dimension The extraction fluid (pH 4.2 ± 0.05) is made of two inorganic acids (nitric and sulfuric acid) to simulate acidic rainwater.

2.3.3 The US EPA Multiple Extraction Procedure (MEP)

The MEP simulates leaching caused by the repetitive precipitation of acid rain water (EPA Method 1320). MEP may be used to address long-term leachability. MEP is designed to simulate the leaching that a waste will undergo from repetitive precipitation of acid rain on an improperly designed sanitary landfill. The repetitive extractions will give the highest concentration of each constituent that is likely to leach in a natural environment. This test utilizes an initial acetic acid extraction (pH 5 ± 0.2) followed by sequential extractions with simulated acid rain So, MEP combines aspects from both the TCLP and the SPLP. Extraction on the first day calls for TCLP extraction fluid at a

liquid-to-solid ratio of 20:1; thereafter, the procedure calls for SPLP extraction solution (pH 3 ± 0.2) (at least eight subsequent extractions) at the same liquid-to-solid ratio. Details are discussed in Chapter 3.

2.4 Leaching Tests for Assessing the Potential for Groundwater Contamination

Leaching of pollutants to groundwater is a very complex process influenced by several factors such as meteorological parameters (e.g., rainfall), soil properties (particle size distribution, organic carbon content), and physical-chemical characteristics (Kördel and Klein 2006).

Regulation of groundwater quality is generally under state jurisdiction; most states have their own risk-based regulatory thresholds regarding contaminant transport from soil to groundwater. The state of Florida has what are known as Soil and Groundwater Cleanup target Levels (SCTL and GWCTL). The SCTLs consist of over 350 individual chemicals with pre-calculated total constituent concentration thresholds based on-direct human contact with soil and potential for soil contamination to migrate to groundwater. Different limits reflect different possible groundwater uses. The worst case scenario is where the water is assumed to be used for direct human consumption.

The GWCTLs are a similar list of maximum leachable concentrations for various constituents. For particularly hazardous constituents, the US EPA primary and secondary drinking water standards (Table 2-3) are generally used for the GWCTL. SCTL were developed based on direct human contact (i.e., direct exposure), and based on soil acting as a source of groundwater or surface water contamination (i.e., leachability). The US EPA has developed measurements of cancer potency of carcinogens, which are termed cancer slope factors (CSFs). Risk-based soil cleanup guidelines have been developed for both carcinogens and non carcinogens. For non-

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cancer risks, the reference dose (RfD) is the term used to refer to the maximum acceptable exposure. RfD's are determined from Lowest Observed Adverse Effect Level (LOAEL) or No Observed Adverse Effect Level (NOAEL) measurements that have been multiplied by a series of uncertainty factors. There are separate RfDs for different pathways of exposure (Oral, inhalation). For calculating SCTL, we need to consider different pathways (ingestion, inhalation, dermal exposure). As for example, equation for a cancer risk from soil exposure through ingestion will be, CTL (mg/Kg) = {Target Cancer risk X Body weight (Kg)}/ {Oral Cancer Slope Factor $(mg/kg\text{-}day)^{-1}$X ingestion rate (mg/day)}.

The formula for calculating GWCTL (carcinogen) is, GWCTL (mg/L) = {Target Cancer risk X Body weight (Kg)}/ {Oral cancer slope factor $((mg/kg\text{-}day)^{-1}$ X Average Water Consumption Rate (L/day)}.

Body weight and water consumption are assumed for calculation. For non carcinogen it will be only, GWCTL= {(RFDX Body Weight)/Water consumption rate}. Since metals present in land-applied solid waste may leach from the waste and migrate to the groundwater (Townsend et al. 2003), possible risk to ground water should be assessed. In Florida and many other states, leaching risk is evaluated by conducting the SPLP and comparing the results to the aforementioned risk-based groundwater standards. This approach is typically viewed as being more representative because the chemical nature of the waste, which can impact leaching, is tested.

2.5 Characteristics of Phosphogypsum

The chemical and mineralogical characteristics of phosphogypsum vary depending upon the nature of the phosphate ore, the type of process used in fertilizer manufacturing, the efficiency of plant operation, the age and location of the stockpile,

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and any contaminants which may be introduced into the phosphogypsum at the production plant (Arman and Seals 1990). Calcium and sulfate dominate the composition of phosphogypsum because it is approximately >90% gypsum (Berish 1990). PG normally has a pH between 4.5 and 5.0. Acidity of PG is due to residual phosphoric acid, sulfuric acid and fluoride acids contained within the pore spaces. May and Sweeney (1984a) found the pH of extracts from Florida phosphogypsum to range between 2.1 and 5.5. Metal concentrations in PG have been thoroughly characterized and typical concentrations are summarized in Table 2-4. These elemental compositions may vary greatly depending on the source of the phosphate rock.

2.6 Phosphogypsum Leaching Studies

The leaching behavior of materials depends on several parameters. These include specific element solubility and availability or release potential. Again solubility can be influenced by pH, complexation by inorganic species or dissolved organic matter, and reducing properties (Kim 2002).

May and Sweeney (1984a) investigated nine PG stacks in Florida to study various physical and chemical characteristics of PG. Results for this analysis showed that the trace elements were uniformly distributed within the PG stacks. May and Sweeney (1984b) evaluated the leachability of Ra and elements the EPA has classified as toxic (As, Ba, Cd, Cr, Pb, Hg, Se, and Ag) by using the standard EPA 'EP' extraction procedure (Federal Register 1980). The concentrations of toxic elements in the extract were all below EPA maximal concentrations, therefore the material was considered non-toxic by EPA standards. The authors estimated that the inclusion of Ra into the phosphogypsum crystal structure would be 89% of the amount originally present, indicating that very little Ra would be leached. They concluded that phosphogypsum

could not be classified as a hazardous waste because it was neither corrosive nor caustic (pH was > 2 and < 12.5). In addition the average total elemental concentrations of elements classified as toxic by the EPA were less than the EPA allowable toxic elemental criteria for toxic hazardous waste (Federal Register 1980).

Rusch and Seals (2004) conducted TCLP on raw PG and oven dried PG samples (oven-dried at 45°C for 12 hours and ground to pass through a US Standard sieve No.10.) collected from Louisiana. The metal concentrations in the leachate from both type, were also well below the US EPA toxicity characteristics limits. Also, there was no significant difference between these two types of samples.

Kendron (1996) conducted EPTOX and TCLP on raw PG specimens to understand the leaching behavior of As, Ba, Cd, Cr, Pb, Ag, Hg and Se through phosphogypsum. The results indicated a potential leaching of these species. Although, the leachate concentration levels were below the US EPA toxicity limits, the concentrations failed to meet the US EPA drinking water limits for several species.

To determine the potential environmental impact of phosphogypsum, Naff (1984) conducted EPTOX on phosphogypsum. The results were within the permissible EPA limits for toxicity; however SO_4^{2-} and fluoride levels exceeded drinking water standards. Haridasan (2002), conducted leaching studies on PG samples (Kochi, India) using distilled water (pH 6.0) and rainwater (pH= 5.0–5.8) as leachants. They varied contact time and solid/liquid ratio in the leaching procedures. The laboratory results indicated that rainwater leached less ^{226}Ra than distilled water.

The leachability of Cd, Cu, U and Zn in Syrian PG was studied by Al-Masri et al. (2004). They did leaching test of PG with distilled water and concluded that Cu and Cd

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are easily transferrable to water or surrounding environment. They also grouped PG into six different particle sizes to observe the effect of particle size on leachability and found that fine particles (45–75 mm) yielded a relatively high solubility.

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Table 2-1. Active phosphate rock mines in the United States in 2007 (USGS 2007)

Owner	Mine	State
CF Industries, Inc.	South Pasture	Florida
Mosaic Co, The	Four Corners	Florida
Do	Hookers Prairie	Florida
Do	Hopewell	Florida
Do	South Fort Meade	Florida
Do	Wingate Creek	Florida
Nu-West Industries, Inc. (Agrium Inc.)	Dry Valley	Idaho
P4 Production, LLC. (Monsanto Co.)	South Rasmussen	Idaho
PCS Phosphate Co., Inc.	Aurora	North Carolina
Do	Swift Creek	Florida
Simplot, J.R., Co.	Smoky Canyon	Idaho
Do	Vernal	Utah

Table 2-2. RCRA toxicity characteristics limits (metals only)

Metal	RCRA TC Limit (mg/L)
As	5.0
Ba	100
Cd	1.0
Cr	5.0
Hg	0.2
Se	1.0
Ag	5.0
Pb	5.0

Table 2-3. US EPA drinking water standards

Primary		Secondary	
Contaminant	Standard (mg/L)	Contaminant	Standard (mg/L)
As	0.01	Al	0.2
Ba	2.0	Cu	1.0
Be	0.004	Fe	0.3
Cd	0.005	Mn	0.05
Cr	0.1	Zn	5
Cu	1.3	Cl^-	250
Pb	0.015	SO_4^{2-}	250
Sb	0.006	TDS	500
Se	0.05		
Tl	0.002		

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Table 2-4. Content of some trace elements in Phosphogypsum (PG) produced from different rock phosphate sources; also included are typical literature values for soil

Element	Florida Source PG[a]	Idaho Source PG[b]	South African Source PG[c]	Tunisian Source PG[d]	Typical soil[e]
			mg/Kg		
Ag	<1	1-11			0.05
As	40	<1-2			7.2
Au (μg/kg)		3-15			
B	3	<10-30			33
Ba	7	20-140	140		580
Be	1	1-2			0.92
Br		1-2			0.85
Cd	7	9-28		40	0.35
Cl		<100-300			100
Co	2	<1		8	9.1
Cr		<10-70			54
Cu	8	10-42	103	6	25
Hg (μg/kg)			<50	14000	90
Mn	15	<2-10			550
Mo	16	<1-2		5	0.97
Ni	2	3-15		15	19
Pb	1	3-7	13		19
Rb		<10-20			67
Sb	100	0.3-0.8			0.66
Se		4-67			0.39
Sr	10	610-670			240
Th		<1			9.4
U		6-13			2.7
V	19	10-40			80
Y	2	100-120	50		25
Zn	9	18-112	6	315	60
Zr	10	<10-110	185		230

[a]May and Sweeney (1984a)
[b]Luther and Dudas (1993)
[c]Malan (1988)
[d]Rouis and Bensalah (1990)
[e]Sposito (1989)

CHAPTER 3
METHODS AND MATERIALS

3.1 Overview

To assess the leachability of various trace metals from phosphogypsum (PG), samples were extensively analyzed with respect to composition and leaching behavior. Inorganic element concentration from acid digestion and leaching samples were analyzed using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES).This section will describe the preparation of the samples and methods that were followed to carry out the leaching tests.

3.2 Sample Collection and Processing

PG was sampled from the top of a PG stack located in Mulberry, Florida. Samples were collected from four locations: the north, south, east, and west walls of the top stack. Samples were retrieved from depths of 1 to 2 feet from the top of the stack. PG samples were named north wall (NW), south wall (SW), east wall (EW) and west wall (WW) based on their locations. PG samples were collected by using cleaned scoops, trowels, shovels, and were placed in five-gallon buckets (HDPE) then sealed with lids. PG samples were then transported to the UF laboratory. A total of 330 kg of PG was collected from each of the four sampling locations. In the lab, samples collected from different locations were not mixed together. But samples collected from different depths for each location were thoroughly mixed to get a homogenous sample for that location Samples were stored in closed containers in the lab at room temperature. To perform research on PG, the requirements of 40 CFR 61.205 were followed; all PG was accompanied by certification documents that conformed to the requirements of 40 CFR 61.208. The total quantity of PG at a facility did not exceed 7000 lbs. Containers of PG

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were labeled with the following warning: “Caution: Phosphogypsum Contains Elevated Levels of Naturally Occurring Radioactivity”.

3.3 Leaching Procedures

Four regulatory-based leaching tests were performed-TCLP, SPLP, EPTOX, and MEP. The TCLP, SPLP, EPTOX, and MEP were developed by the US Environmental Protection Agency (EPA). In addition, several experiments were conducted in a similar fashion as TCLP but substituting actual landfill leachates and DI water as the leaching solution.

3.3.1 Toxicity Characteristic Leaching Procedure

The TCLP method is defined in EPA Method 1311.TCLP uses one of two different extraction fluids, depending on the alkalinity of the waste. Extraction fluid 1 is prepared by diluting a mixture of 11.4 mL acetic acid (CH_3COOH) and 128.6 mL of 1N sodium hydroxide (NaOH) to 2L deionized water (DI). The resulting solution pH is 4.93 ± 0.05. Extraction fluid 2 is used for highly alkaline materials. This solution is prepared by adding 11.4 mL acetic acid to 2L deionized water. pH of this solution should be 2.8±0.05. Because the pH of the PG sample was less than 5, extraction fluid 1 was used. The TCLP requires that samples first be size-reduced to less than 0.95 cm in any dimension. One hundred grams of the size-reduced samples were placed in a 2.2-L TCLP extraction vessel, and 2.00 L of the extraction solution were added. The slurry was mixed on a rotary extractor for 18 ± 2 hr at 30 ± 2 revolutions per minute and then filtered through a 0.7 μm glass fiber filter. The filtrate was collected in 500 mL plastic bottles (HDPE) and preserved by adjusting the pH to less than 2 using nitric acid. The leachates generated by the TCLP process were acid digested and analyzed using ICP-AES.

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3.3.2 Synthetic Precipitation Leaching Procedure

SPLP leachates were prepared according to the procedure outlined in EPA method 1312. A concentrated SPLP solution was prepared by adding 100 mL of one percent (by volume) solution of concentrated nitric acid and 100 mL of one percent solution of concentrated sulfuric acid, and then combining these in a 2 parts nitric to 3 parts sulfuric ratio (40%:60%). Then, 0.4 - 0.5 mL of concentrated SPLP solution was added to reagent water in a 2-L volumetric flask and diluted to 2-L. The resulting SPLP solution pH was required to be 4.20 ± 0.05. The SPLP requires that samples first be size-reduced to less than 0.95 cm. One hundred grams of the size-reduced samples were placed in a 2.2-L SPLP extraction vessel, and 2 L of the SPLP solution were added. The slurry was mixed on a rotary extractor for 18 ± 2 h. After the extraction procedures, separation of the leachate solution from PG was completed using a vacuum filtration set-up. The filter used was a 0.7 μm acid-washed glass fiber filter .The rotary extractor was used during the TCLP and SPLP tests was designed to rotate eight 2-L bottles in an end-over-end fashion. When loaded with a full load, each extractor rotates at 30 rpm as required by the TCLP and SPLP procedures. The filtrate was collected in 500-mL plastic bottles and preserved by adjusting the pH to less than 2 using nitric acid.

3.3.3 Extraction Procedure (EP) Toxicity Test Method

The method is defined in EPA Method 1310b.This test requires the continual addition of acid to maintain a constant extraction pH. For the EPTOX, 100 g of sample were placed in 1.6 L of deionized water and agitated for 24 hours. The method requires that the pH of the mixture be maintained at 5 ± 0.2 by adding 0.5N acetic acid. The PG samples in this study did not require any further acid addition. After 24 h of extraction,

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deionized water was added to bring the total volume of the extraction fluid to 2 L. The leachate was filtered using 0.45-μm filter.

3.3.4 Multiple Extraction Procedure

This test utilizes an initial acetic acid extraction followed by sequential extractions with simulated acid rain. The initial extraction fluid is the same as the EPTOX. The simulated rainfall extraction solution is similar to the SPLP leaching fluid but with a pH of 3.0 ± 0.2. This synthetic acid rain extraction fluid was prepared by adding 60% sulfuric acid and 40% nitric acid (weight percent) to distilled deionized water until the pH is 3.0 ± 0.2. The residual solids after the extraction were re extracted nine times consecutively using synthetic acid rain extraction fluid. An initial sample size of 12.5 g was used. Each extraction step is performed at an L/S ratio of 20:1 for 24 h. After each filtration, both the filter and the sample were added to the next extraction vessel. The final pH values of leachates and metal ion concentrations were determined for each extraction.

3.3.5 Batch Leaching Test with MSW Leachate

This batch leaching test mimicked the condition that MSW landfill leachate directly contacts PG and measured any constituent change before and after mixing MSW leachate with PG. This test method is similar to the TCLP or SPLP test except that it uses MSW landfill leachate as the extract solution. A 100 g sample of PG was mixed with 2 L of MSW leachate and mixed for 18 ± 2 hours using a rotating shaker at 30 rpm. The mixture of MSW landfill leachate and PG was filtered using 0.7 μm glass fiber filter after the rotation. Inorganics were analyzed after acid digestion. For this test, MSW landfill leachate was obtained from Polk County North Central landfill. The pH of leachate was 7.6 and totals dissolved solids (TDS) was 6300 mg/L.

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3.3.5.1 Sulfate analysis

Sulfate concentration in leachate samples from batch leaching test of PG (with MSW leachate) was determined using a spectrophotometer (DR/4000 UV-VIS, HACH, Loveland, CO) with HACH Method 8051. A sample cell was filled with 25 mL of sample. One SulfaVer® 4 reagent powder was added to the cell. Sulfate ions in the sample react with barium in the SulfaVer® 4 and form a precipitate of barium sulfate. The amount of turbidity formed is proportional to the sulfate concentration.

3.3.5.2 Total dissolved solids (TDS)

Total dissolved solids (TDS) of the leaching solution from the batch leaching test with MSW leachate was determined following EPA method 160.1. For this, aluminum weighing dishes were placed in an 180°C drying oven one day before the test. Desiccators were used to cool the dishes. Pre-dried dishes were weighed. A total of 100 mL sample was filtered using vacuum filtration. Filtrates were placed into an oven at 95°C for 18 hours to allow the samples to evaporate to dryness. After 18 hours, temperature was increased to 180°C and continued at least for another 4 hours. The dishes are removed from the oven and placed in the desiccators to cool for 30 minutes. Then the dishes were returned to the 180°C oven for 1-2 hours and weighed. This drying and weighing cycle was repeated until the last two weighings differ by less than 0.5 mg. Dishes were then placed in the desiccators to cool for at least one hour. Then the dish containing the oven-dried sample was weighed to the nearest 0.1 mg. TDS was determined using Equation 3-1.

$$TDS\left(\frac{mg}{L}\right) = \frac{\{[\text{final wt.of dried residue + dish (g)}] - [\text{wt.of dish (g)}]\} \text{ x } 1000000}{\text{Volume of sample (ml)}} \quad (3\text{-}1)$$

3.3.6 Batch Leaching Test with DI Water

This test is similar to TCLP/SPLP except DI water was used as the leaching solution. For this batch test 100 grams of PG was mixed with 2 L of DI water in a 2.2 L glass jar. The mixture was agitated using a rotator for 16 to 20 hrs. After tumbling, the slurry was filtered to separate PG leachate from the slurry. Then samples of this PG leachate was retained for the chemical analysis.

3.4 Total Metal Analysis

Samples were digested to prepare them for trace metal analysis. The leaching test samples from various batch tests were digested according to US EPA Method 3010. To determine total metal concentration of PG, samples were digested according to the US EPA 3050B. Digestion procedure was used to prepare aqueous leachate samples that may contain insoluble colloidal particles for analysis by Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP-AES). Leached and digested samples were analyzed using ICP-AES as per US EPA SW846 method 6010B.

For digestion of aqueous samples nitric acid is added to a specified volume (50 mL) to the sample. The sample is refluxed with additional portion of nitric acid until the digestate is clear or the color is stable. When the digestate reduced to a low volume, it is then finally refluxed with hydrochloric acid and brought up to volume. The digested sample is than analyzed by ICP-AES.

For digestion of solid PG, 1 gram (dry weight) sample was digested with repeated additions of nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). For ICP-AES analyses, hydrochloric acid (HCl) is added to the final digestate and the sample is refluxed.

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3.5 pH of Phosphogypsum

The pH values of PG samples were determined by EPA method 9045D. For this, 20 grams of PG was mixed with 20 mL of reagent water and stirred continuously for 5 min. Then it was allowed to stand for 1 hour. After that, pH was measured.

3.6 Quality Assurance and Quality Control

All sampling equipment and containers were cleaned and prepared according to the US EPA established standards. In the laboratory, analysis blanks, duplicates and calibration check samples were analyzed as appropriate. For total metal analysis every digestion event included (approximately 20 samples) a blank sample, a duplicate sample, a triplicate sample, a matrix spike, a matrix spike duplicate for digestion. All regulatory batch leaching test were conducted in triplicate. However for digestion, a blank, duplicate sample, a sample spike and a sample spike duplicate were included.

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CHAPTER 4
RESULTS

4.1 Total Metal Analysis Results

The chemical composition, which was determined using the US EPA Method 3051b, of the PG samples from each location is shown in Table 4-1. Samples were analyzed for 23 metals (silver, aluminum, arsenic, boron, barium, beryllium, calcium, cadmium, cobalt, chromium, copper, iron, potassium, magnesium, manganese sodium, nickel, lead, antimony, selenium, tin, vanadium and zinc.). Calcium was the most abundant metal detected in PG and ranges from 113,220 (± 58,100) to 171,200 (± 25,900) mg/kg. The minor constituents of raw PG were Al, Fe and K which each had a concentration that exceeded 100.0 mg/kg. Trace elements, such as As, B, Ba, Cr, Cu, Mn, Pb , Sn, V and Zn were also present. Ag, Cd, Co, Mg, Mo, Na, Ni, Sb and Se were not detectable in the samples that were tested. For PG metal analysis, triplicate samples from each location were analyzed. Of the RCRA TC limit metals, barium had the highest concentration (38.6 mg/Kg). Concentrations of other toxic metals (As, Cr, Pb) were below 3 mg/Kg. To use PG beneficially, to where direct human contact with the PG is possible, comparison with risk based standards is needed. Although risk assessment through direct exposure is not the focus of this research, it is discussed briefly as it would certainly need to be considered as part of any beneficial use application. Table 4-3 compares the concentration for each metal with its respective Florida's risk based soil cleanup target level. Florida's SCTLs examine direct exposure in two scenarios, residential and industrial settings. Of the metals detected in PG, the 95% Upper Confidence Limit (UCL_{95}) of only one metal (arsenic) was slightly above its SCTL for residential exposure but below the industrial limit. UCL_{95} was calculated using

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samples from all four locations. In Table 4-1, the average concentrations with standard deviations for each PG sample are presented. Detailed total analysis results are given in Appendix B.

4.2 pH of Phosphogypsum

The pH of PG samples used in this study was in the range of 4.5-4.8 (Table 4-2). One PG sample from each location was tested for pH. The pH of DI water used for this experiment was 6.3. Though PG is composed primarily of the slightly soluble neutral salt, calcium sulfate dihydrate, the acidity may be due to residual phosphoric and sulfuric acids plus hydrofluoric and fluosilicic acids (Smith and Wrench 1984).

4.3 Toxicity Characteristic Leaching Procedure (TCLP)

US EPA specifies toxicity characteristic limits based on the metal concentrations in the TCLP leachates. If any listed compound (mentioned in Chapter 2) exceeds the level specified, the original waste is considered hazardous. The TCLP leachates for raw PG were analyzed for trace metals that are on EPA's list of toxicity characteristic elements such as silver, arsenic, barium, cadmium, chromium, lead and selenium. Mercury was not tested in this study. The TCLP was performed on 12 samples (triplicate samples for each of the 4 locations). All the metal concentrations in the TCLP leachate analyzed for each location were well below the respective regulatory levels. TCLP test data are presented in Figures 4-1 through 4-4. Samples whose concentrations are below detection limits are presented in the plots on the MDL (method detection limit) line. In general, barium leached at higher concentrations than chromium. The mean barium concentration of all 12 samples was 0.11 mg/L (0.07–0.16 mg/L).

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4.4 Synthetic Precipitation Leaching Procedure (SPLP)

The average concentrations (from the four samples; each sample was measured in triplicate) of 21 inorganic elements in the extraction fluids from SPLP test were determined. Eleven of them were detected at concentrations above their respective detection limit. As, B, Be, Cd, Co, Pb, Sb, Sn, Sr, V were not detected in SPLP.SPLP results were compared with Groundwater Cleanup Target Levels (GWCTL). Most of the metals were well below GWCTL except for aluminum and iron. Aluminum concentration is greater than the GWCTL for all the samples. Iron concentration is greater than GWCTL for six samples out of twelve. Even though aluminum and iron are the secondary standards, these results may be questioned by a regulatory agency when PG is considered for use in land application. SPLP results are presented in Figures 4-5 through 4-13 and detailed data are given in Appendix C.

Figures 4-14 and 4-15 show the initial and final pH's for the TCLP test and SPLP test, respectively. The final pH in the SPLP test was consistently lower than the TCLP test in terms of final pH. Figure 4-15, which shows the initial and final pH's in the SPLP tests, shows that the final pH's are generally consistent regardless of the location of the sample.

4.5 Extraction Procedure Toxicity

EPTOX was conducted on PG samples of one location (SW) in triplicate and of the 22 metals analyzed aluminum, barium, calcium, chromium, copper, iron, potassium, magnesium, nickel, strontium and zinc were detected. Final pHs of extraction fluids were greater than SPLP but close to TCLP test (Table 4-4). The TCLP extracted slightly higher concentrations of all the metals than EPTOX except copper, nickel and zinc. Both tests use acetic acid as leaching solution but they have different pH. EPTOX

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results are presented in Figures 4-16 through 4-20 and detailed data are given in Appendix E.

4.6 USEPA Multiple Extraction Procedure

The MEP is used to assess long-term leachability of waste by combining aspects from both the TCLP and the SPLP. The method requires sequential extraction of the same waste. With each subsequent extraction, it is usually expected that leaching concentrations will be decreased with time as there are less contaminants available for leaching. As samples from all the locations showed similar leaching concentrations, the MEP was conducted on samples from only one location (SW) in triplicate. Of the 21 metals analyzed only aluminum, barium, beryllium calcium, chromium, copper, potassium, magnesium, nickel, strontium and zinc were detected above their respective detection limit. The barium, copper, magnesium and potassium results are typical of most sequential leaching tests, with the concentrations decreasing with consecutive extractions. However, for other detected metals, an increase in concentration is observed in the second extraction compared to the first extraction. This may be due to the change in pH (Table 4-5). After the initial increase the metal concentration stabilized and began to decrease with subsequent extractions. Results are presented in Figures 4-21 through 4-26.

4.7 Additional Leaching Testing

4.7.1 The Deionized Water Batch Leaching Test

Batch leaching test with DI water was conducted on samples of all four locations in duplicate (Figures 4-27 through 4-31, Table 4-6). Calcium, which was predominant, leached more in DI leachate than SPLP. Average calcium concentration in SPLP leachate is 656 mg/L and 808 mg/L in DI water leachate. Of the 22 metals analyzed

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only aluminum, barium, calcium, copper, potassium, molybdenum, sodium, nickel, strontium and zinc were detected above their respective detection limit. Iron, which was detected both in SPLP and TCLP test, was below its detection limit when leached with DI water. Barium concentration was also higher in both TCLP and SPLP than DI water leaching test. Again, copper concentrations leached by DI water were higher than both SPLP and TCLP. Other than these metals, when PG samples were leached with DI water; extracted concentrations were somewhat similar to the SPLP.

4.7.2 Batch Leaching Test with MSW Leachate

Figures 4-32 through 4-40 present the results of the leaching tests where MSW leachates were used as the extraction fluids. Table 4-7 presents the result of the final pH of MSW leaching solutions. This leaching test was carried out on samples of all four locations in triplicate. Samples were analyzed for 22 metals. Only antimony, copper, selenium and tin were below their respective detection limit. Concentrations of most cations in the MSW leaching solution were similar to those in the MSW leachate except calcium, iron and strontium. While iron concentration decreased after contacting with leachate, strontium concentration increased. Calcium concentrations in MSW leaching solution were up to one order of magnitude greater than those in the MSW leachate. Concentrations of sulfate and TDS in the MSW leachate were compared to those in the original MSW leaching solutions (Figure 4-41 and 4-42). Sulfate concentrations in the leachate ranged from 3,000-3,250 mg/L. These sulfate concentrations are 15 times greater than those in original MSW leachate. TDS measured in the leaching solutions ranged from 9,350-9,500 mg/L. TDS concentration in the original MSW leachate was about 6,300 mg/L.

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Table 4-1. Metal concentrations (mg/kg) of PG samples

Element Detected	Sample ID Mean ± SD (mg/Kg) NW	SW	EW	WW
Ag	BDL[a]	BDL	BDL	BDL
Al	875±77[b]	738±56	625±56	785±55
As	1.9±0.9	1.9±0.7	2.1±1.0	1.7±0.9
B	60±18	57±10	22±2.1	55±16
Ba	48.0±6.4	30.8±2.0	33.4±7.2	42.2±6.6
Be	BDL	BDL	BDL	BDL
Ca	171,200 ±25,900	138,300 ±13,100	147,600 ±36,500	113,200 ±58,100
Cd	BDL	BDL	BDL	BDL
Co	BDL	BDL	BDL	BDL
Cr	1.9±0.4	1.6±0.3	1.5±0.5	1.3±0.5
Cu	2.0±0.8	1.9±0.7	1.9±0.6	1.9±0.5
Fe	903±65	932±130	615±133	717±94
K	126±24	187±31	140±5	175±29
Mg	BDL	BDL	BDL	BDL
Mn	2.0±0.1	4.2±0.4	2.8±0.7	1.7±0.6
Mo	BDL	BDL	BDL	BDL
Na	BDL	BDL	BDL	BDL
Ni	BDL	BDL	BDL	BDL
Pb	3.1±0.6	3.5±0.9	2.8±0.4	2.7±0.6
Sb	BDL	BDL	BDL	BDL
Se	BDL	BDL	BDL	BDL
Sn	6.3±0.8	3.8±1.1	4.0±1.0	3.9±0.4
V	1.6±0.6	2.3±0.6	1.2±0.1	1.3±0.3
Zn	4.2±0.9	4.7±0.8	3.1±0.5	5.3±0.9

[a]BDL = Below detection limit (detection limits are presented in Appendix A)
[b]arithmetic mean ± standard deviation of three replicates

Table 4-2. pH of PG samples

Sample Location	pH
North Wall	4.5
South Wall	4.7
East Wall	4.7
West Wall	4.8

Table 4-3. Total metal comparison with risk based standards for direct exposure

Metal	Mean Concentration ± SD (mg/Kg)	UCL_{95} (mg/Kg)	Florida SCTL Residential (mg/Kg)	Florida SCTL Industrial (mg/Kg)
Al	756±108[a]	817	80000	NA
As	1.9±0.8	2.37	2.1	12
B	48.5±19.8	59.7	17000	430000
Ba	38.6±8.8	43.6	120	130000
Ca	142590±29550	159296	NA	NA
Cr	1.6±0.4	1.82	210	470
Cu	1.9±0.6	2.28	150	89000
Fe	792±166	886	53000	NA
K	157±33.4	176	NA	NA
Mn	2.7±1.1	3.31	3500	43000
Pb	3.0±0.7	3.4	400	1400
Sn	4.5±1.3	5.26	47000	880000
V	1.6±0.6	1.93	67	10000
Zn	4.3±1.1	4.95	26000	630000

[a]arithmetic mean ± standard deviation of all (12) samples

Table 4-4. pH results (Extraction Procedure Toxicity Test)

Sample ID	pH
SW 1	4.71
SW 2	4.69
SW 3	4.72
DI Water	7.20

Table 4-5. pH results (Multiple Extraction Procedure Test)

Extraction Number	pH
1	4.71
2	3.39
3	3.44
4	3.40
5	3.26
6	3.34
7	3.34
8	3.30
9	3.15

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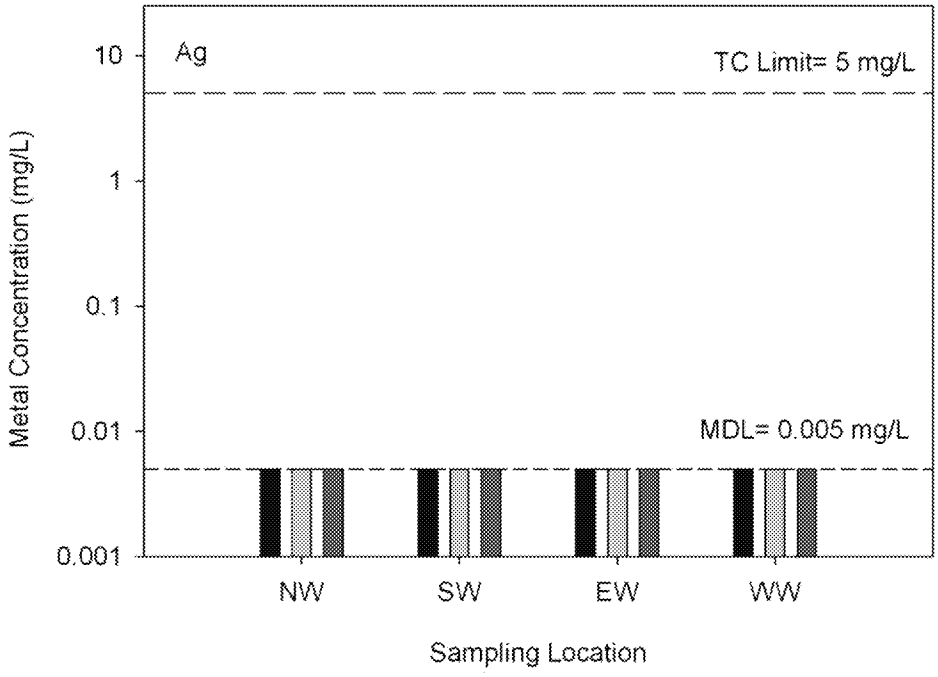
Table 4-6. pH results (Batch leaching test with DI water)

Sample ID	pH
North Wall (NW)	4.53
South Wall (SW)	4.72
East Wall (EW)	4.92
West Wall (WW)	4.78
DI Water	7.4

Table 4-7. pH results (Batch leaching test with MSW leachate)

Sample ID	pH
North Wall (NW)	7.40
South Wall (SW)	7.40
East Wall (EW)	7.60
West Wall (WW)	7.60
MSW Leachate	7.70



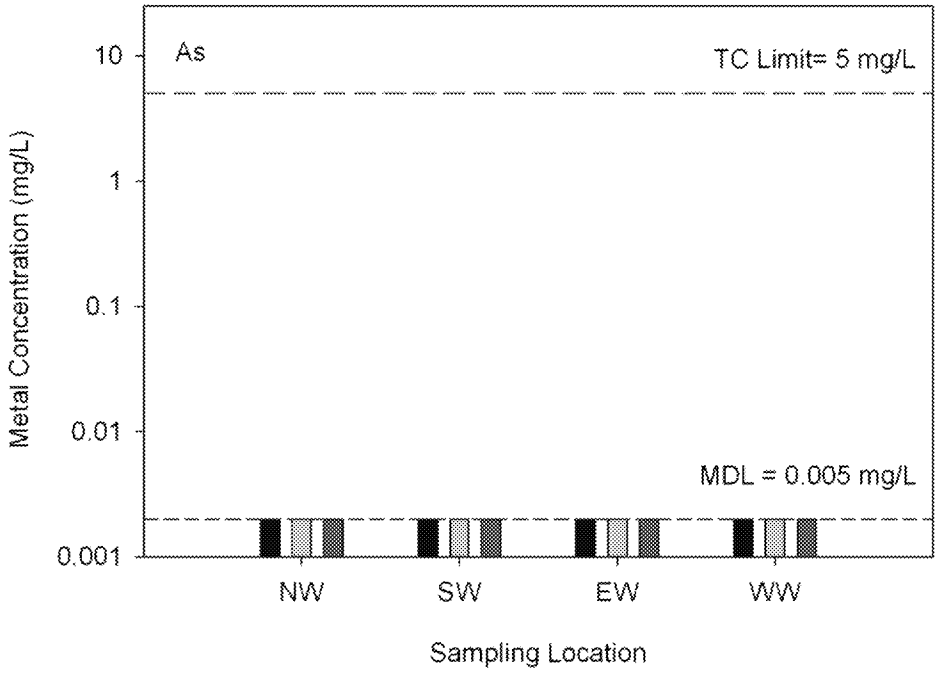
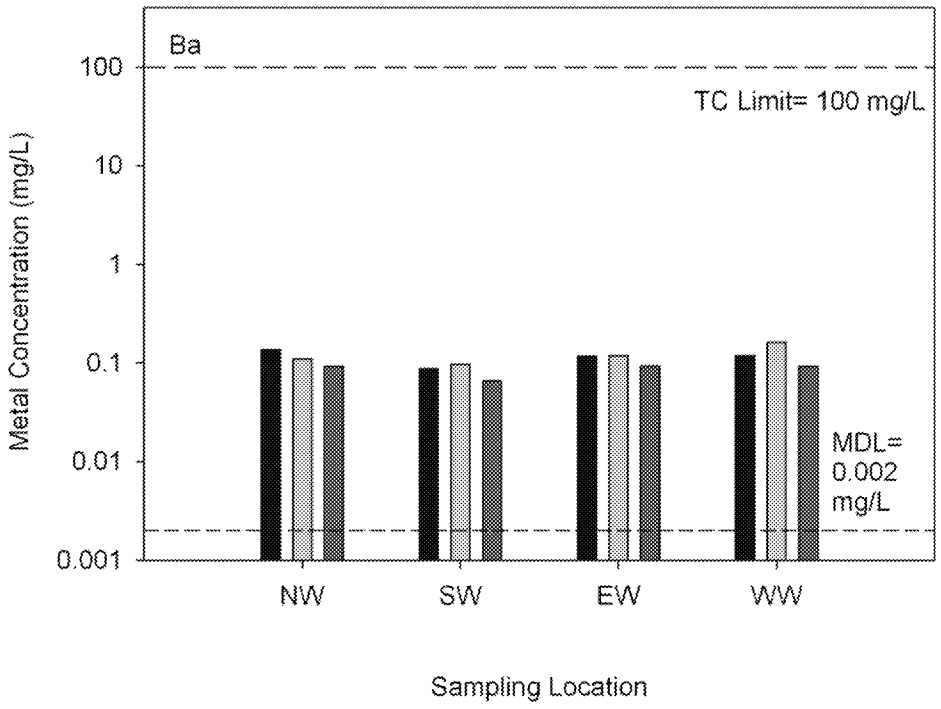


Figure 4-1. Silver (Ag) and Arsenic (As) concentrations of PG samples in TCLP test



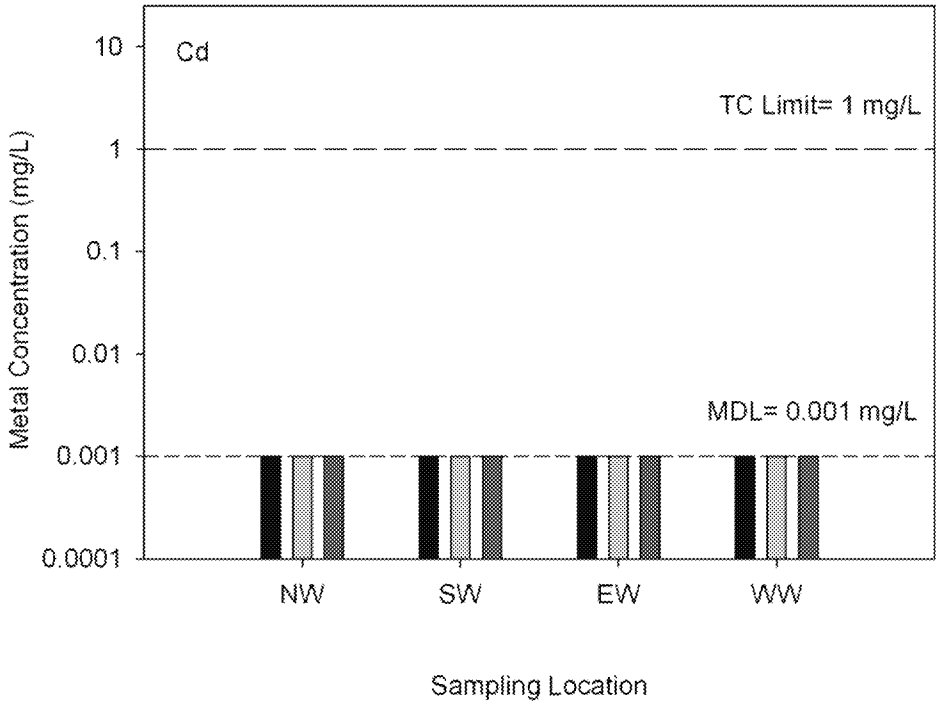
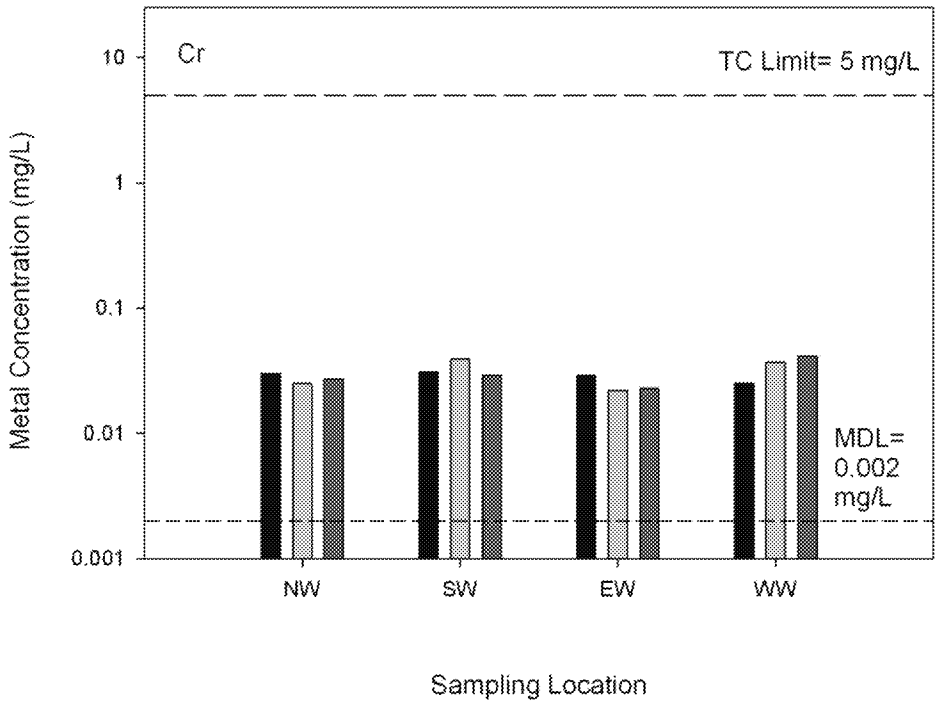


Figure 4-2. Barium (Ba) and Cadmium (Cd) concentrations of PG samples in TCLP test



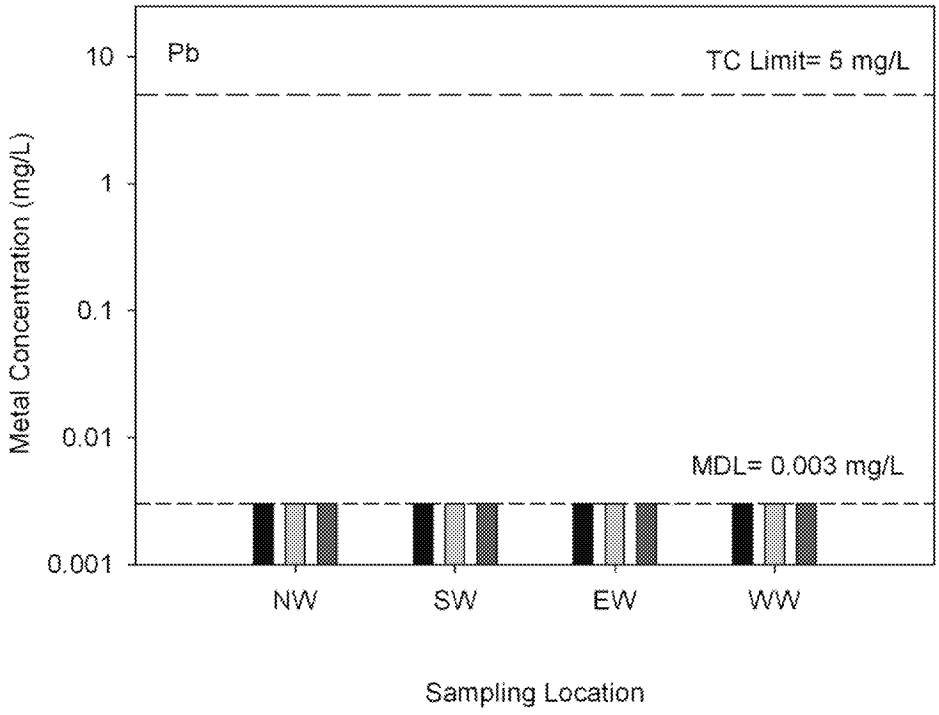


Figure 4-3. Chromium (Cr) and Lead (Pb) concentrations of PG samples in TCLP test

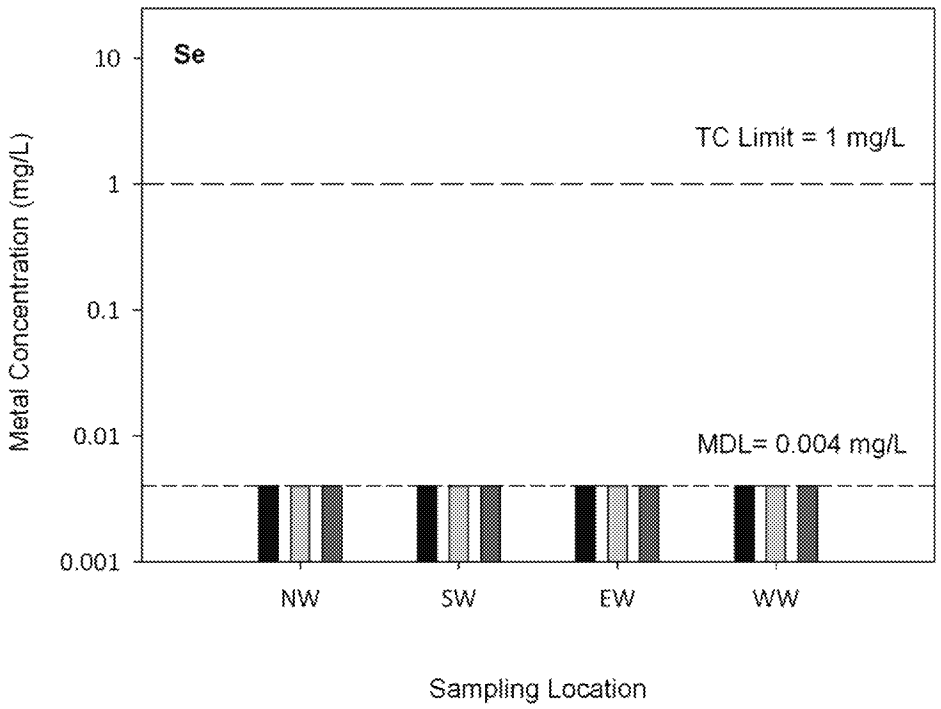
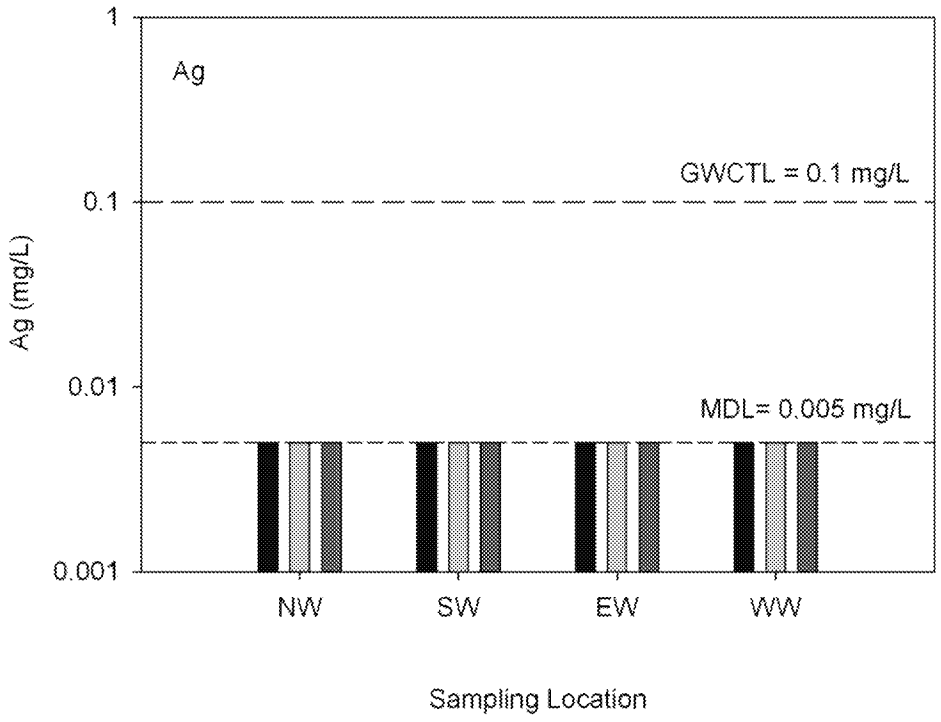


Figure 4-4. Selenium (Se) concentration of PG samples in TCLP test



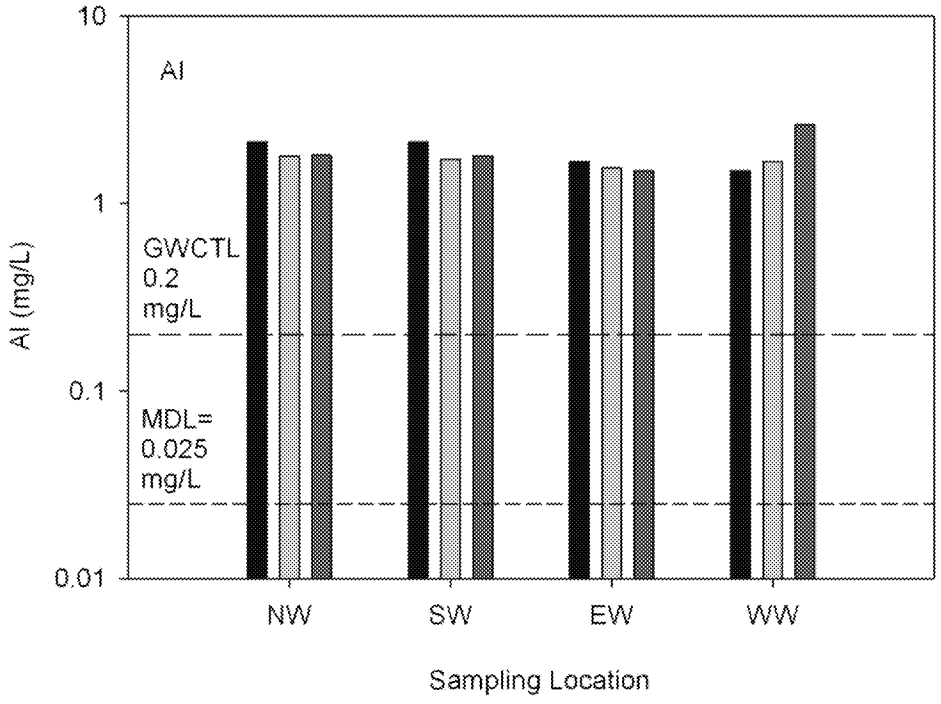
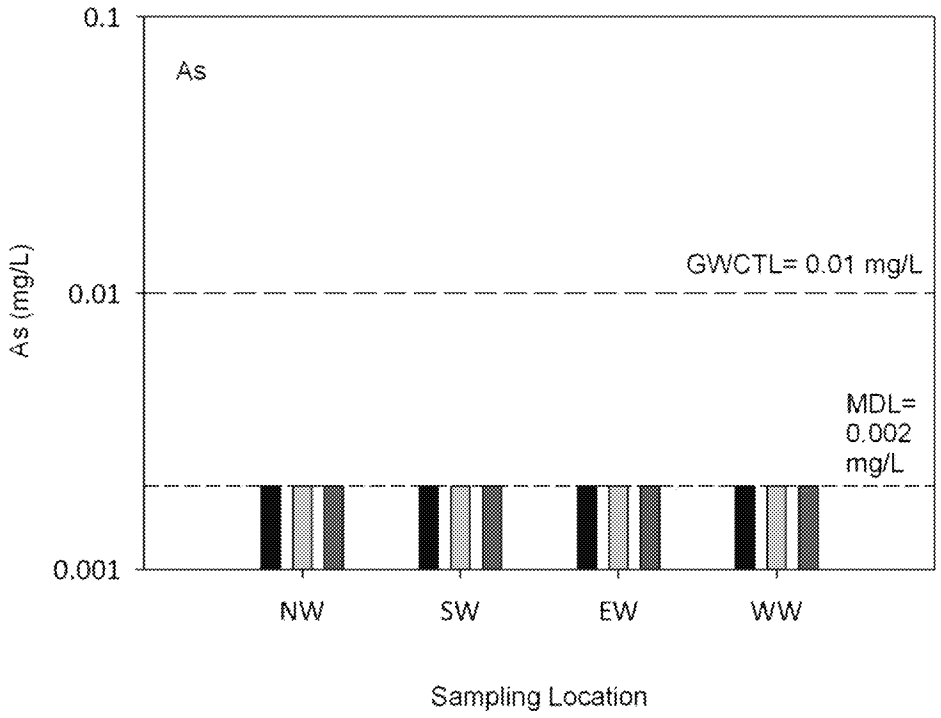


Figure 4-5. Silver (Ag) and Aluminum (Al) concentrations of PG samples in SPLP test



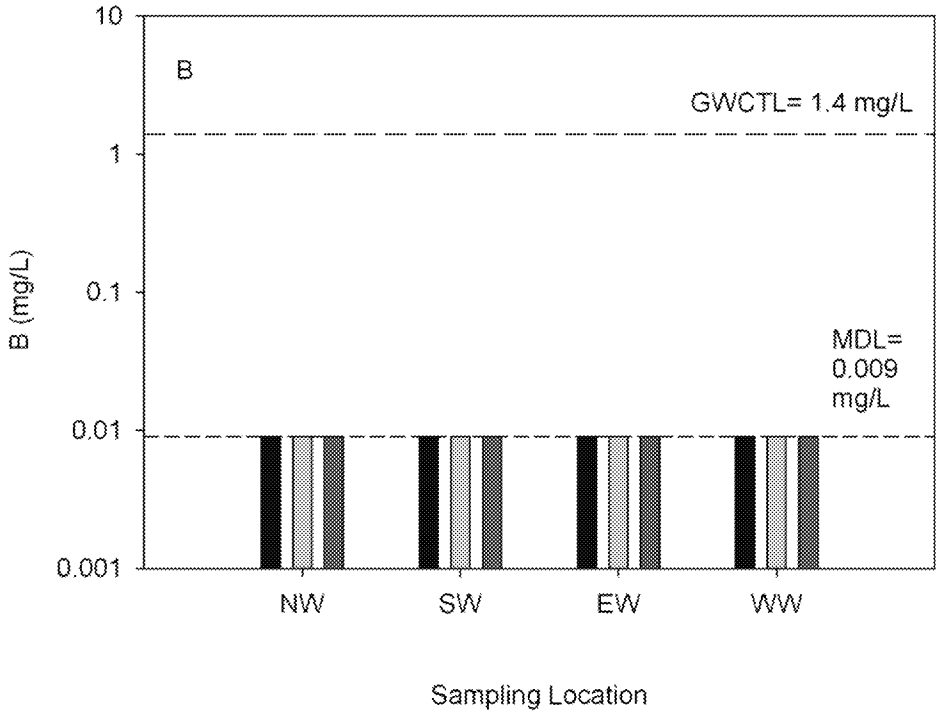
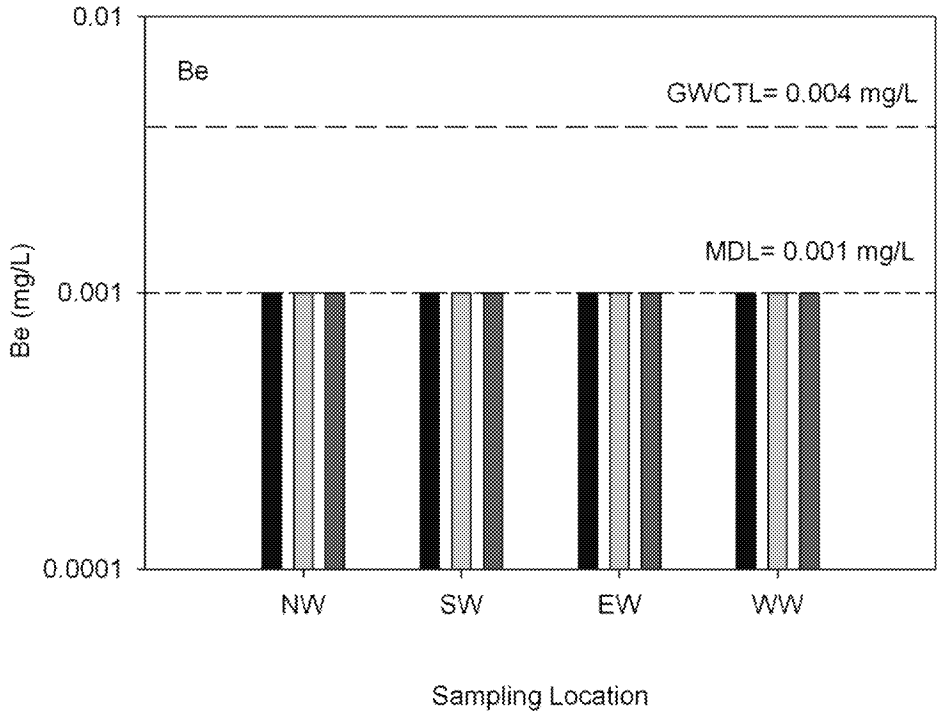


Figure 4-6. Arsenic (As) and Boron (B) concentrations of PG samples in SPLP test



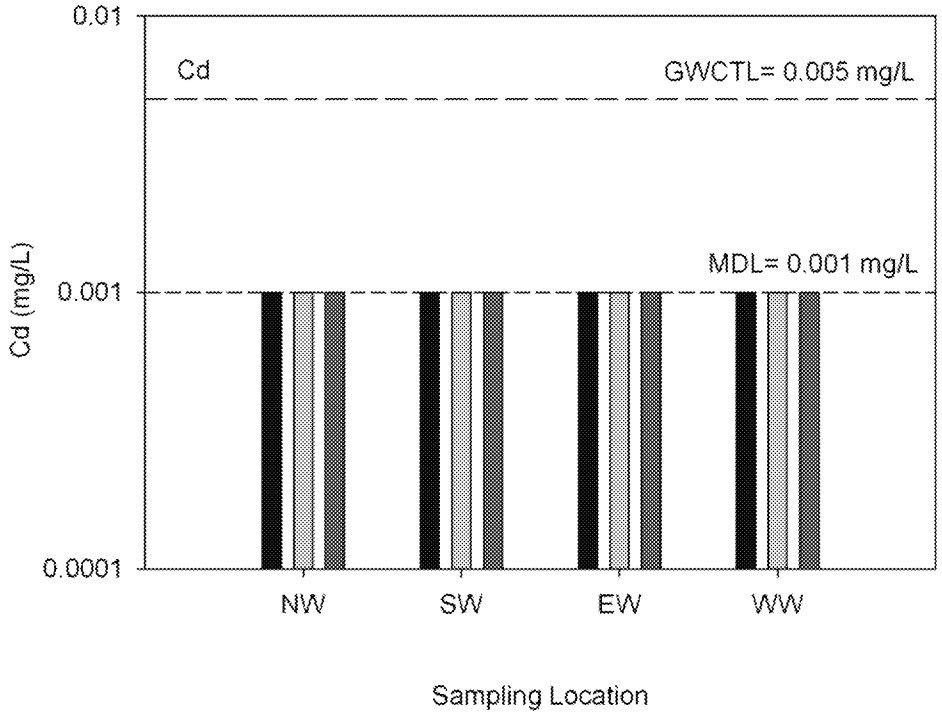
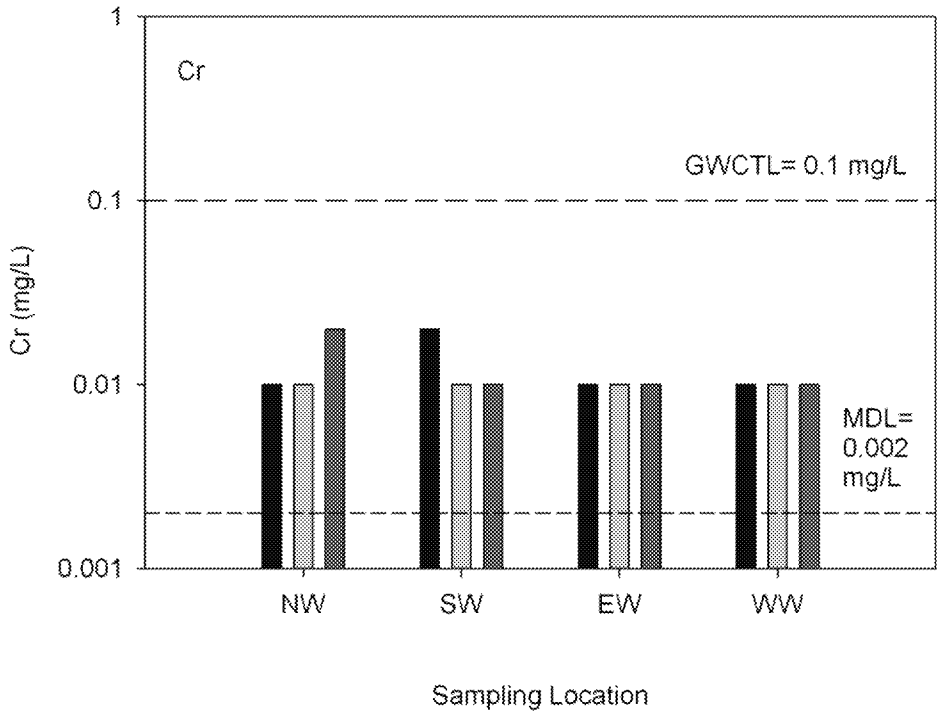


Figure 4-7. Beryllium (Be) and Cadmium (Cd) concentrations of PG samples in SPLP test



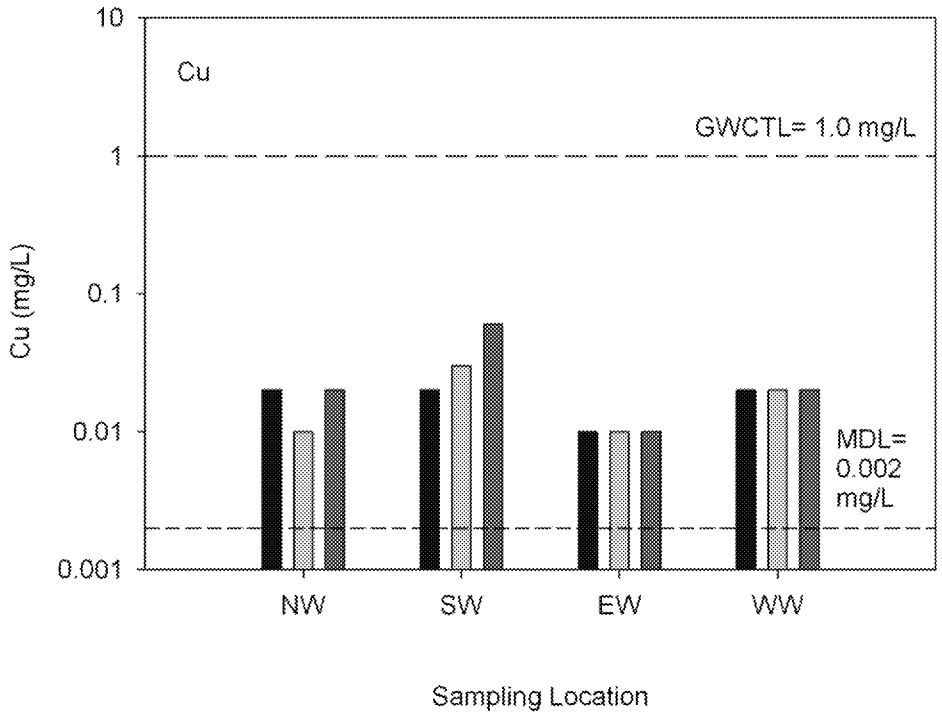
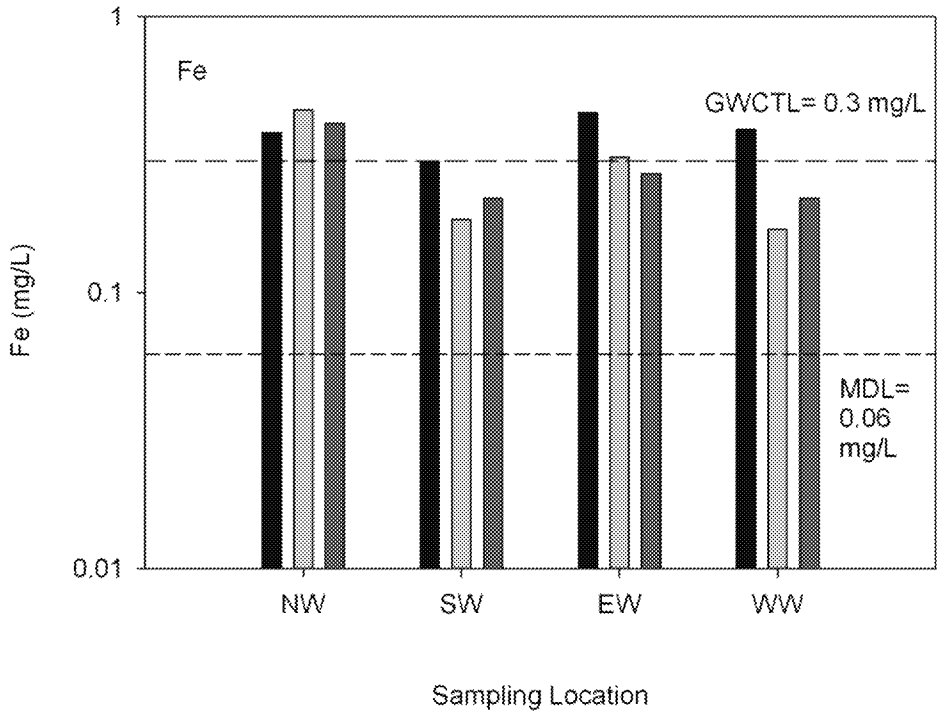


Figure 4-8. Chromium (Cr) and Copper (Cu) concentrations of PG samples in SPLP test



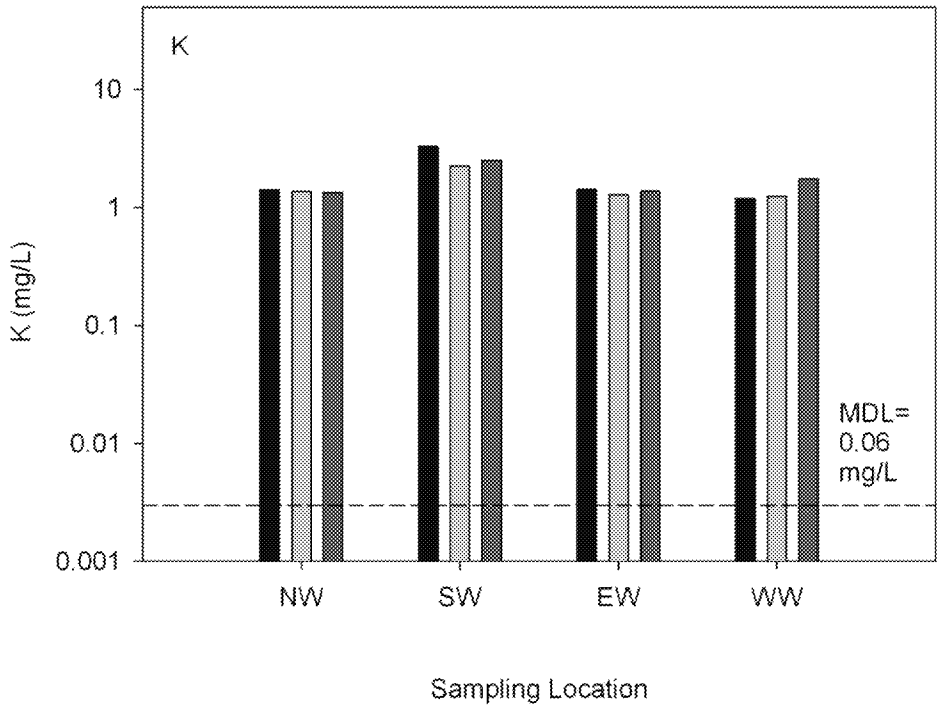
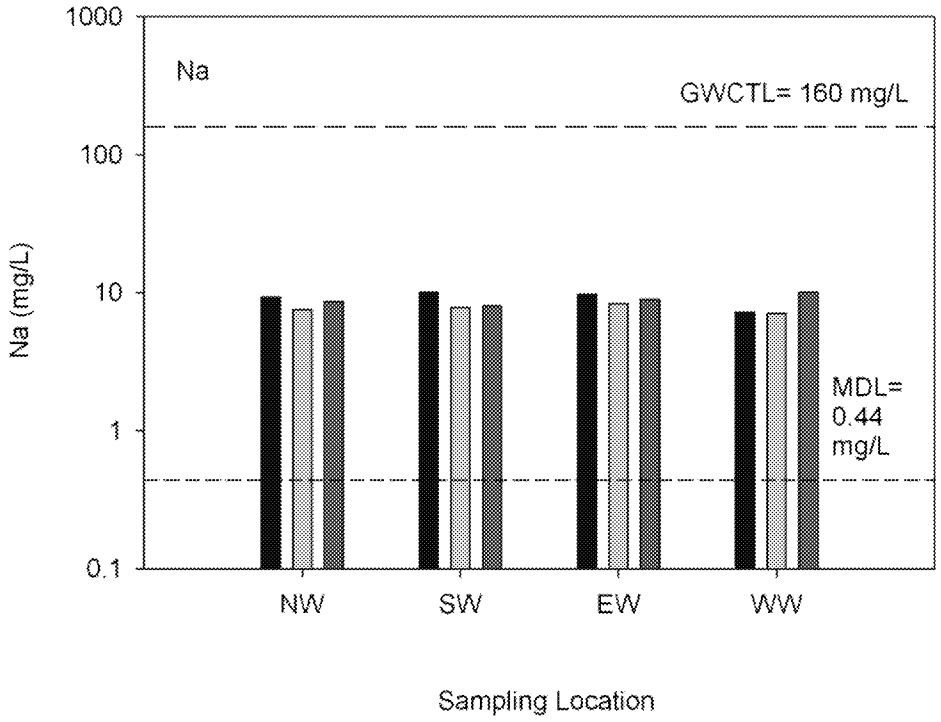


Figure 4-9. Iron (Fe) and Potassium (K) concentrations of PG samples in SPLP test



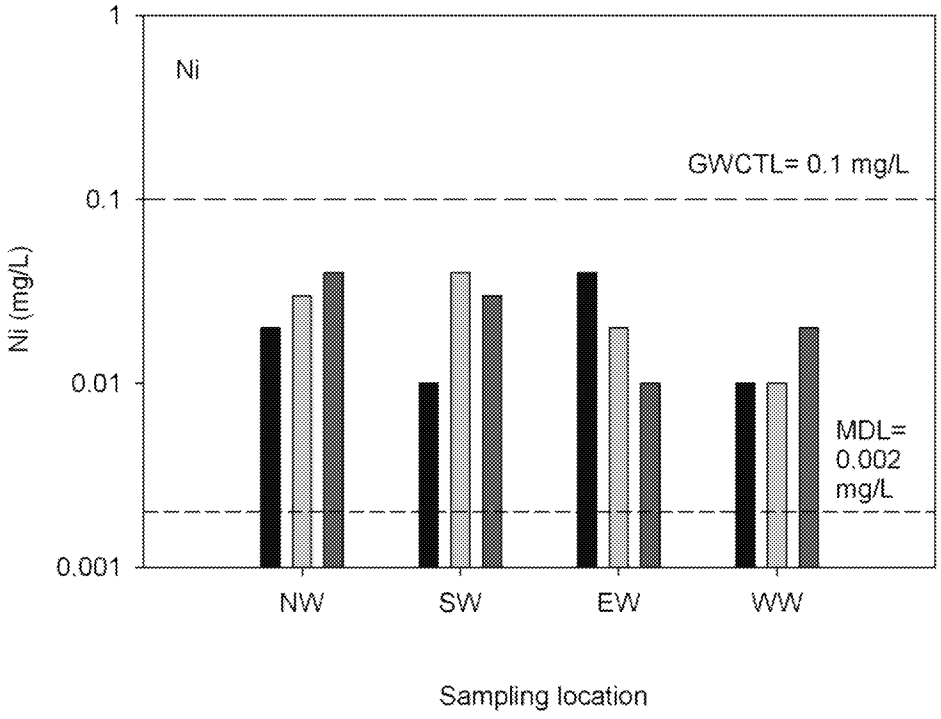
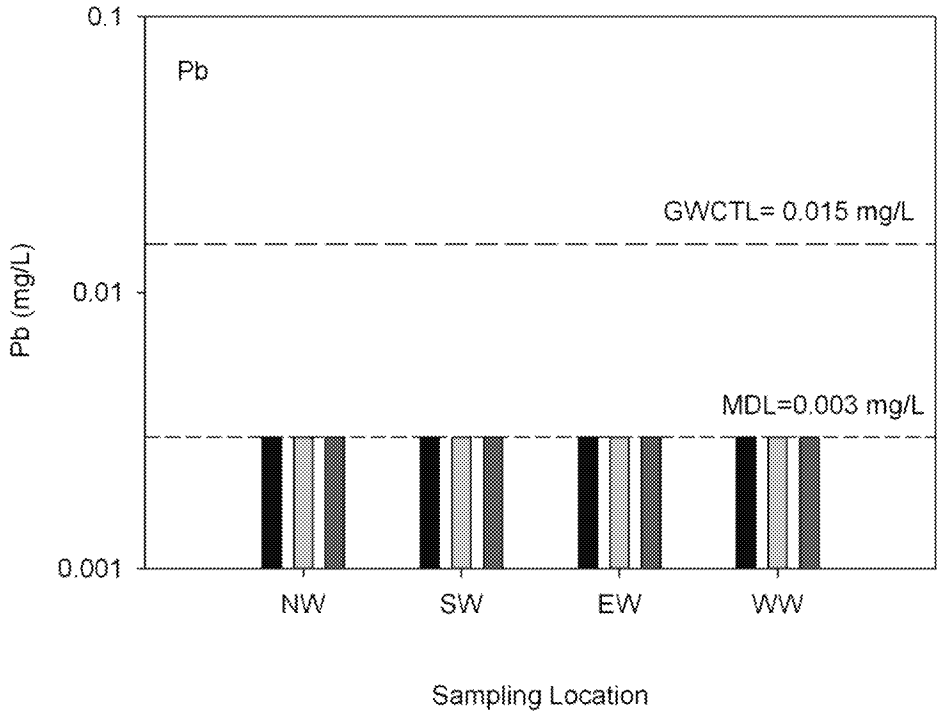


Figure 4-10. Sodium (Na) and Nickel (Ni) concentrations of PG samples in SPLP test



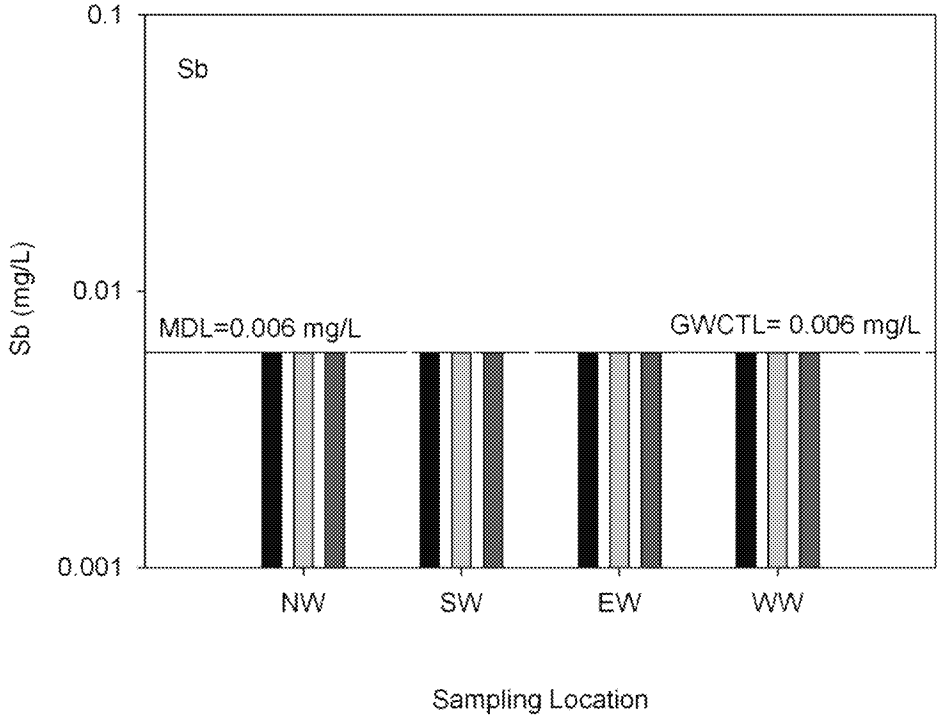
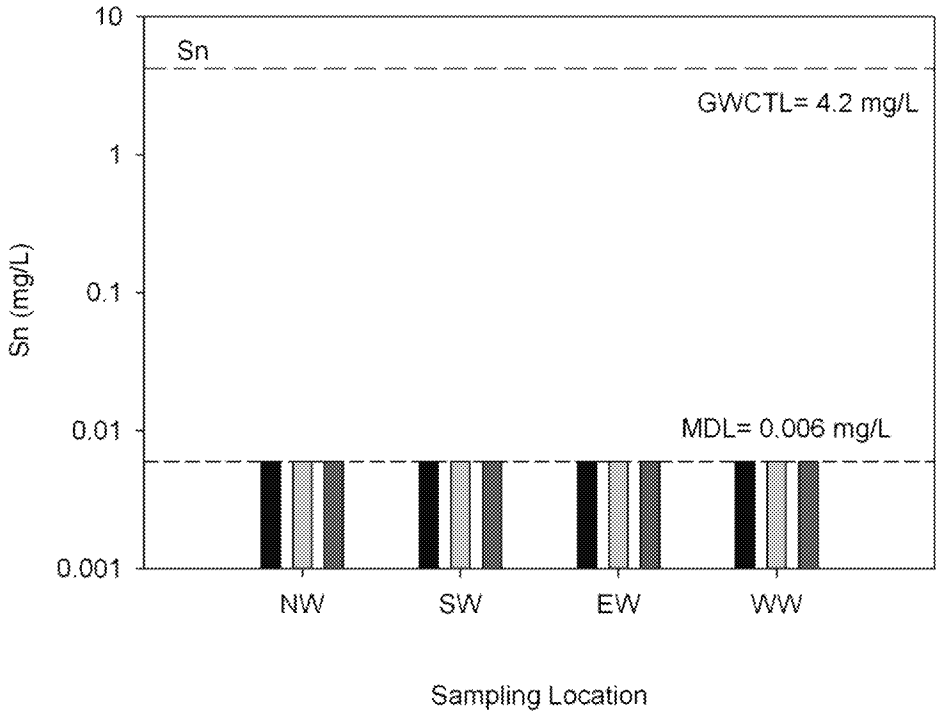


Figure 4-11. Lead (Pb) and Antimony (Sb) concentrations of PG samples in SPLP test



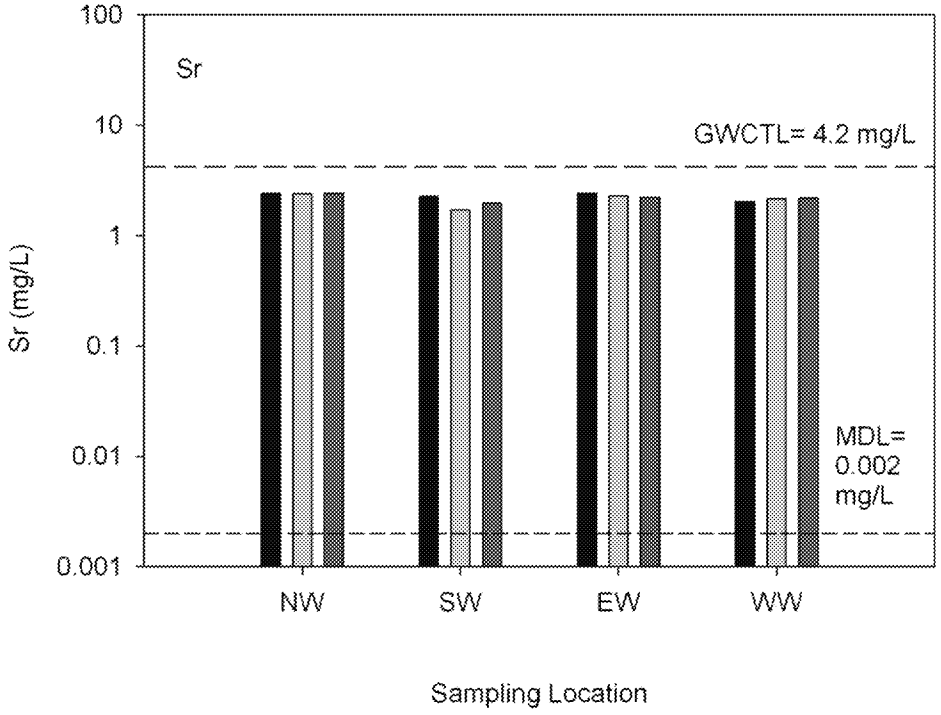
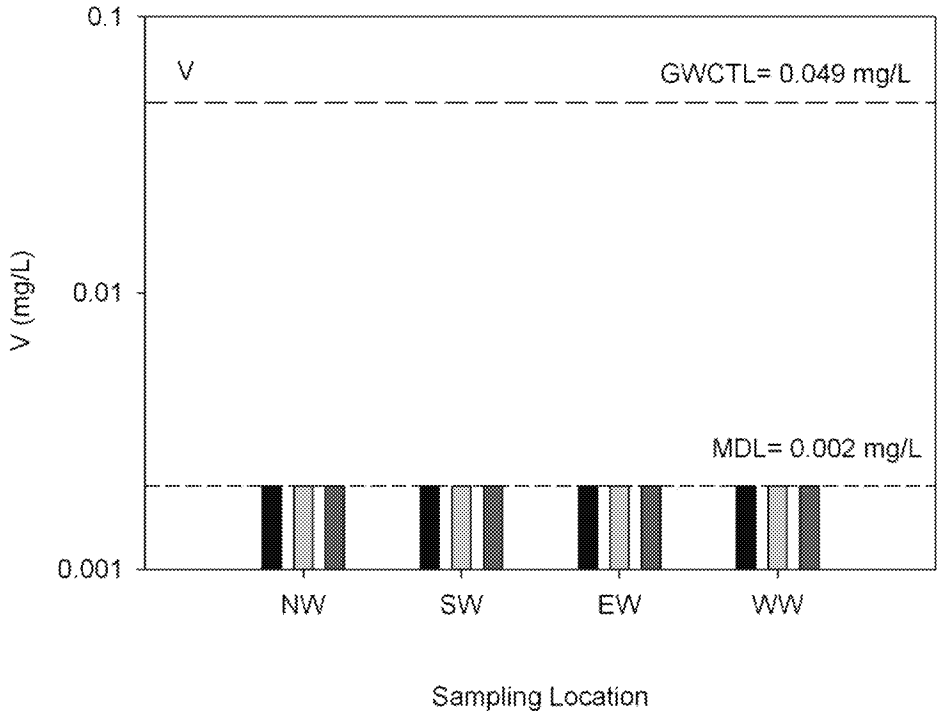


Figure 4-12. Tin (Sn) and Strontium (Sr) concentrations of PG samples in SPLP test



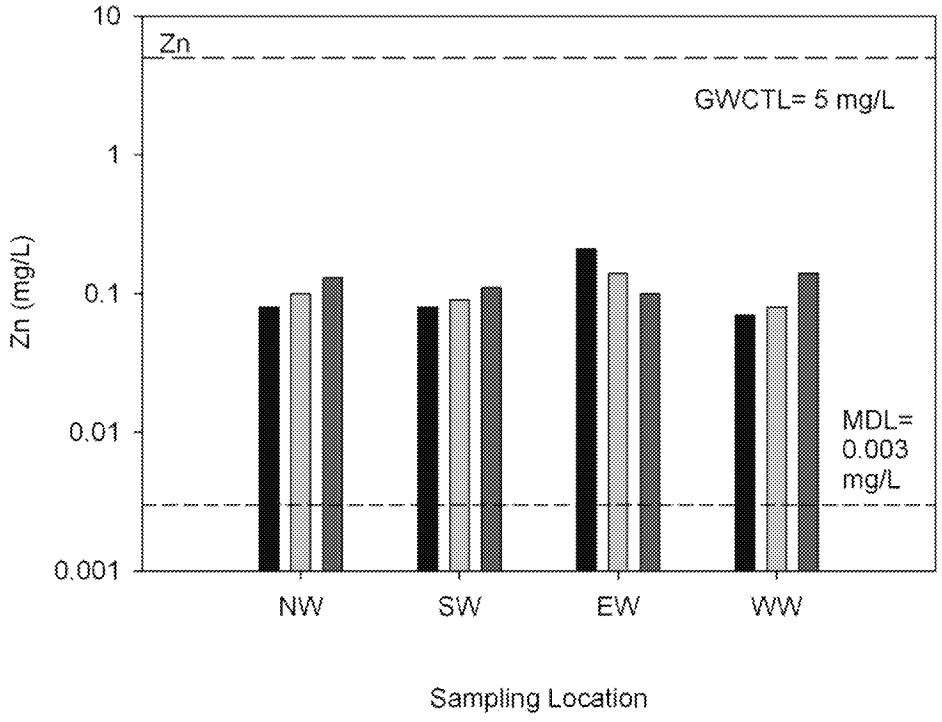


Figure 4-13. Vanadium (V) and Zinc (Zn) concentrations of PG samples in SPLP test

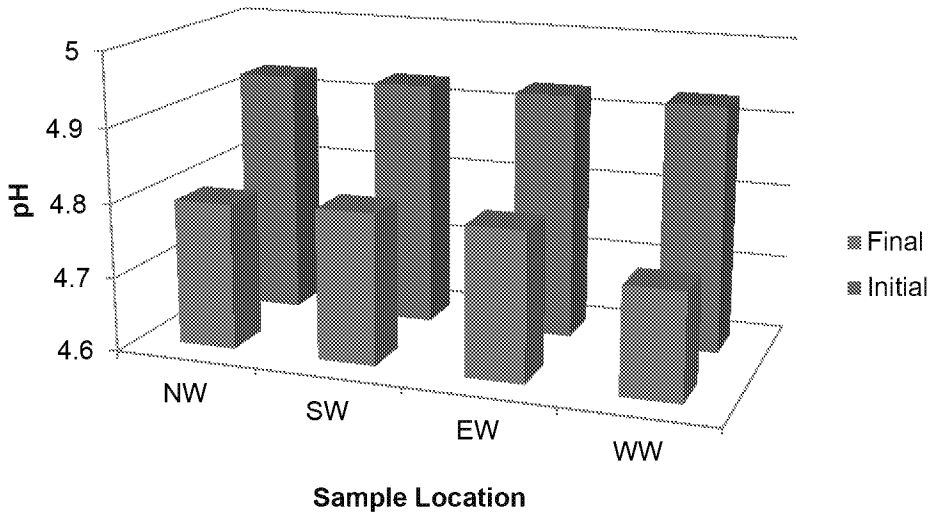


Figure 4-14. Toxicity Characteristic Leaching Procedure initial and final pH

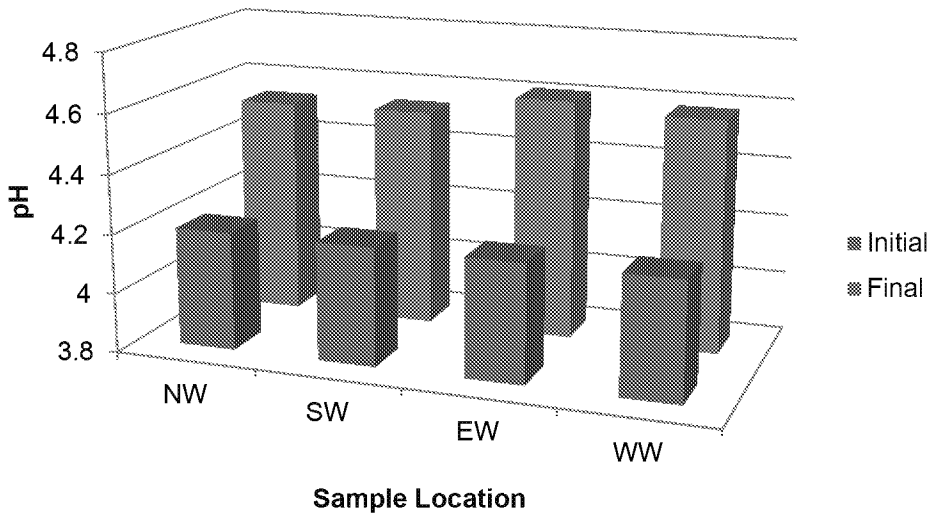


Figure 4-15. Synthetic Precipitation Leaching Procedure initial and final pH

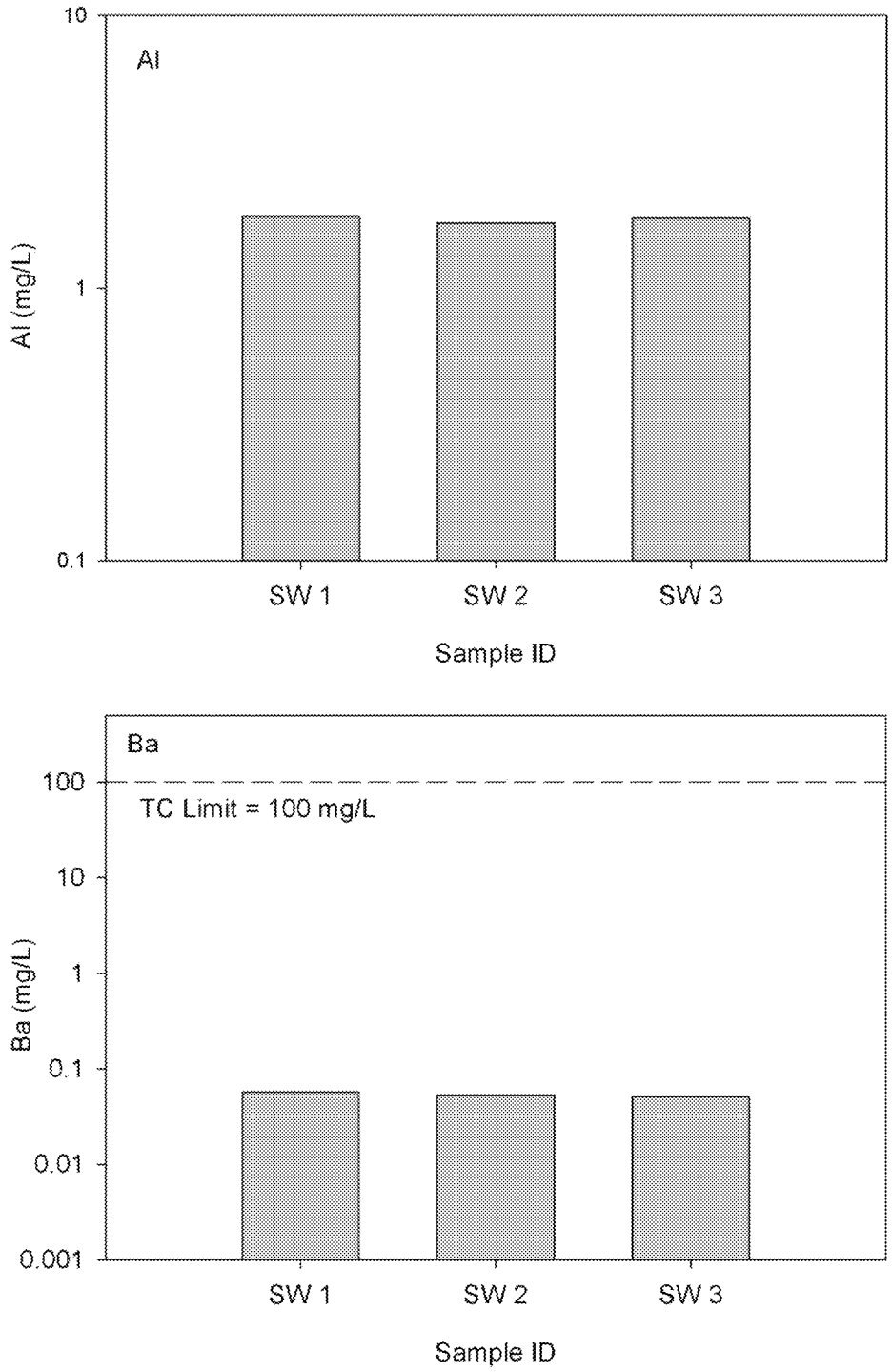


Figure 4-16. Aluminum (Al) and Barium (Ba) concentrations of PG samples (south wall) in EPTOX test

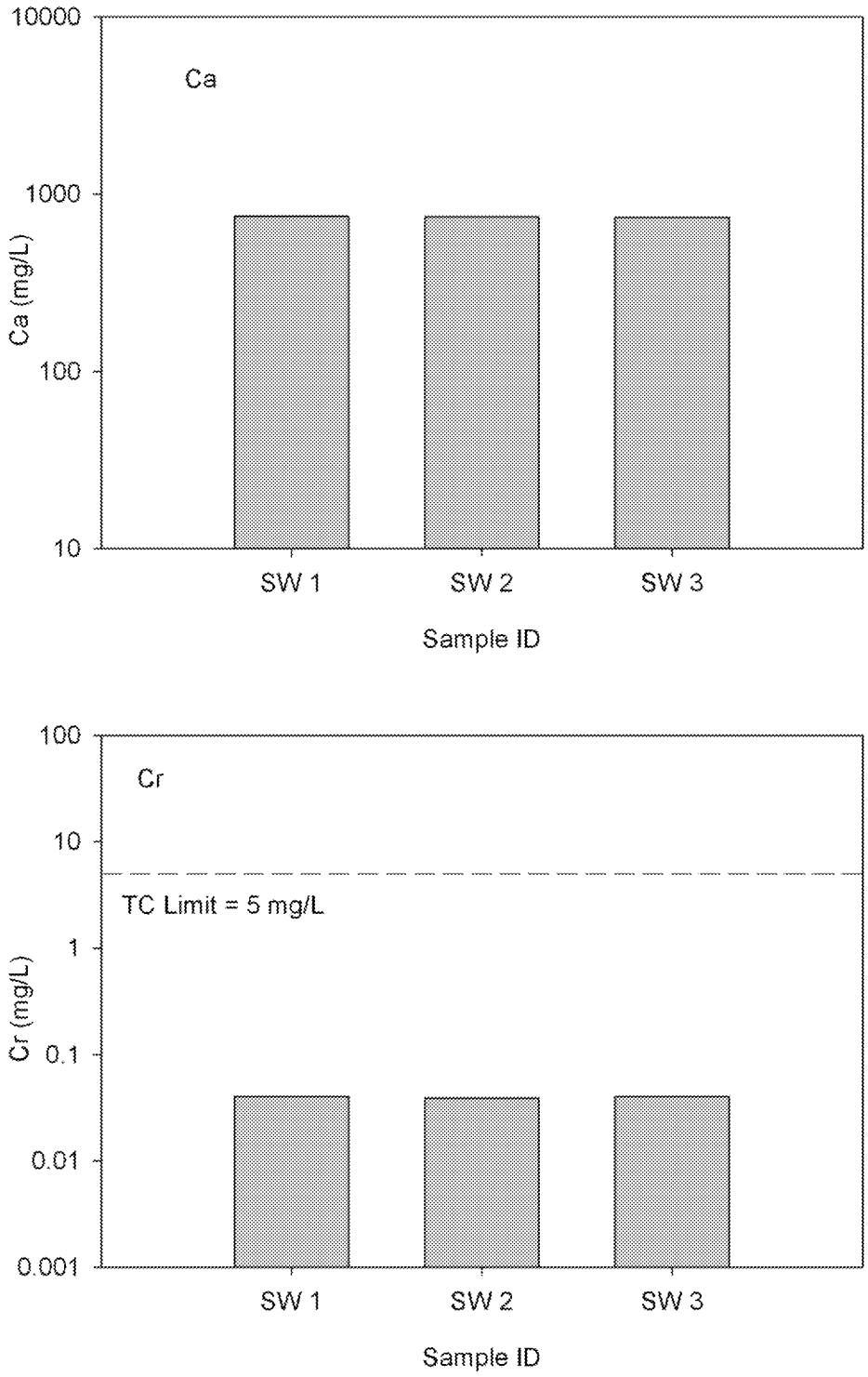
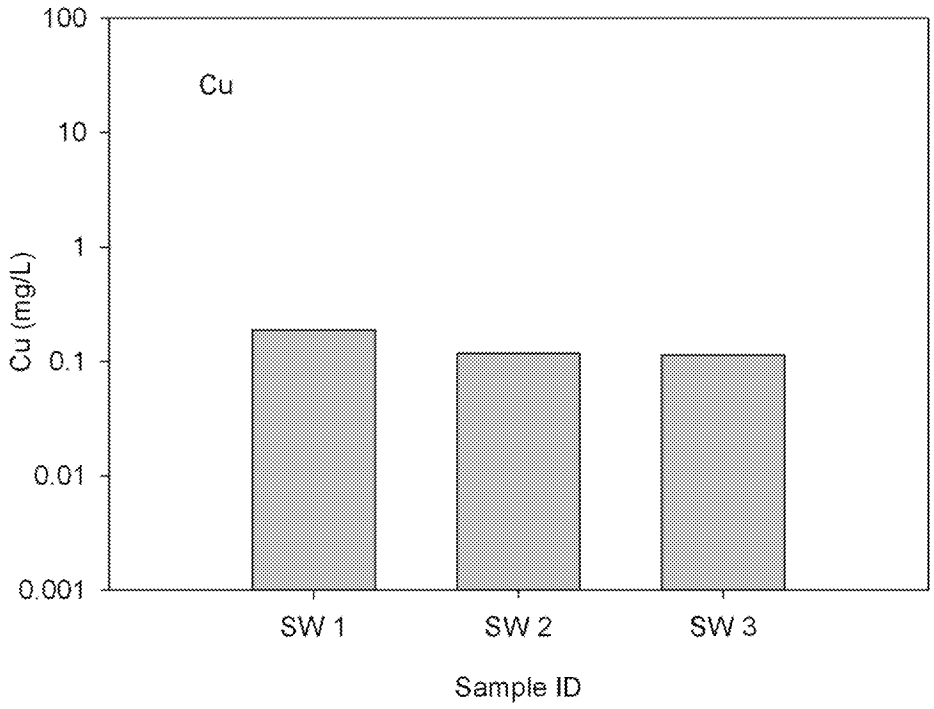


Figure 4-17. Calcium (Ca) and Chromium (Cr) concentrations of PG samples (south wall) in EPTOX test



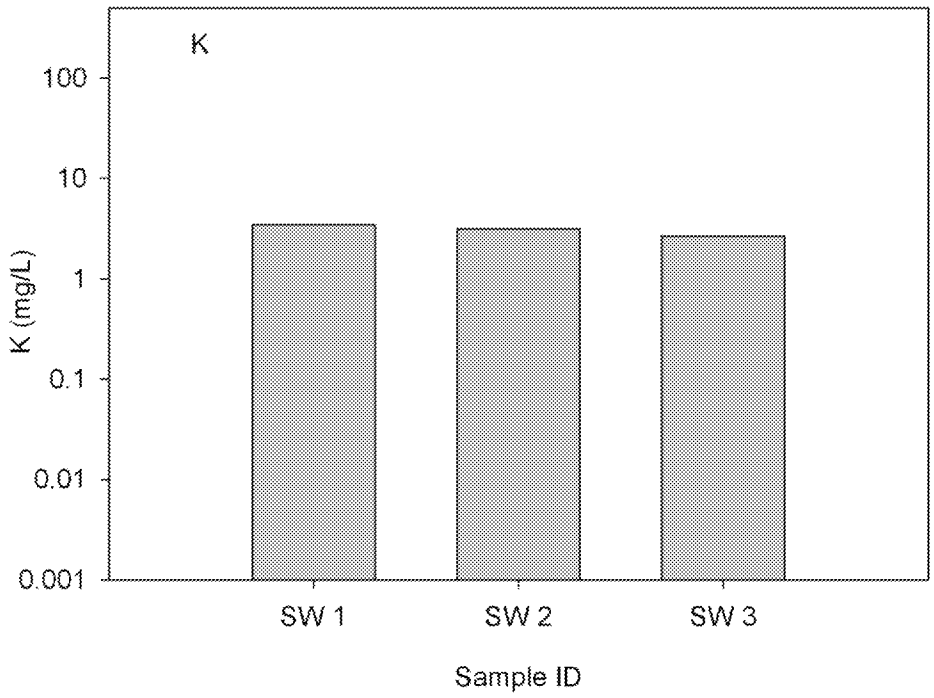
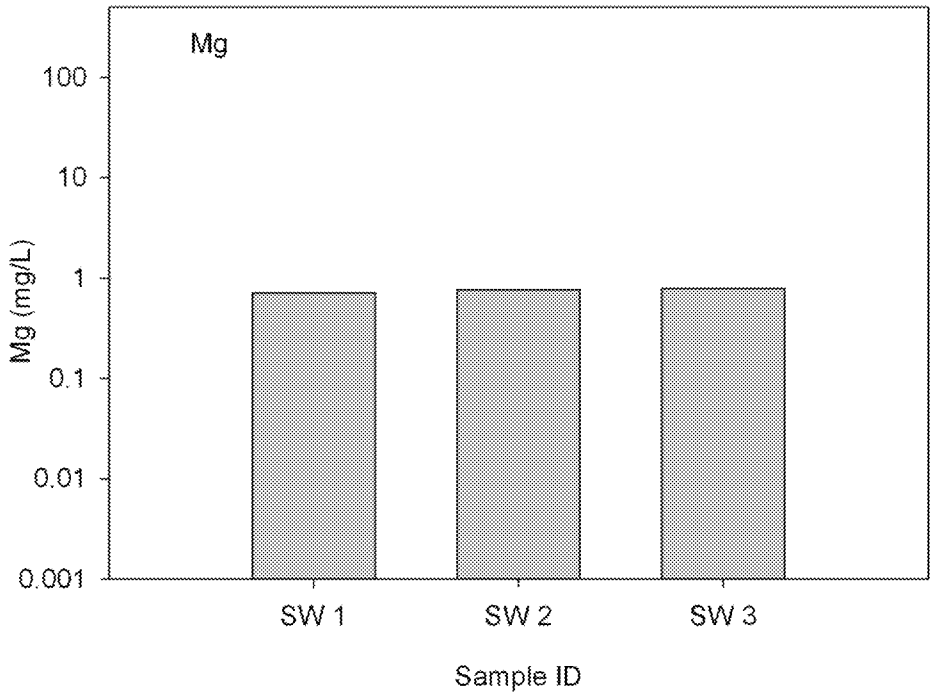


Figure 4-18. Copper (Cu) and Potassium (K) concentrations of PG samples (south wall) in EPTOX test



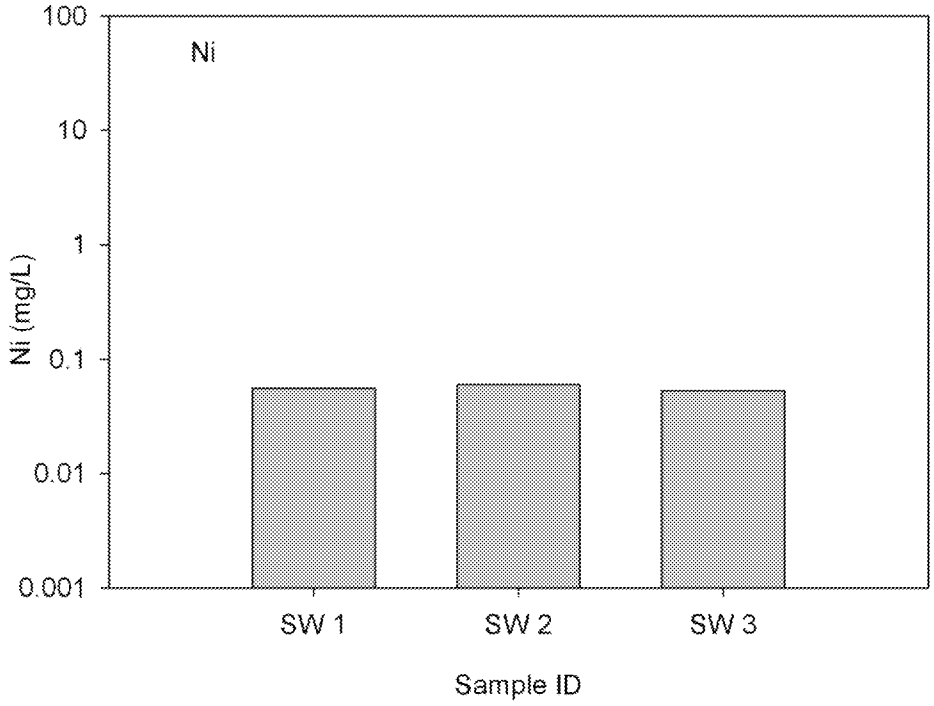
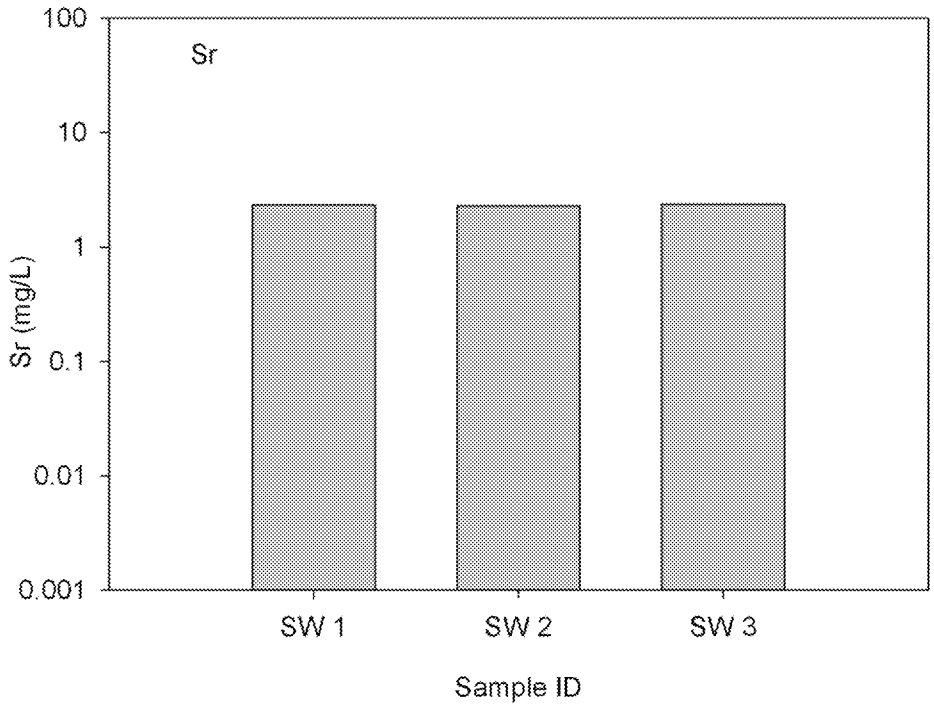


Figure 4-19. Magnesium (Mg) and Nickel (Ni) concentrations of PG samples (south wall) in EPTOX test



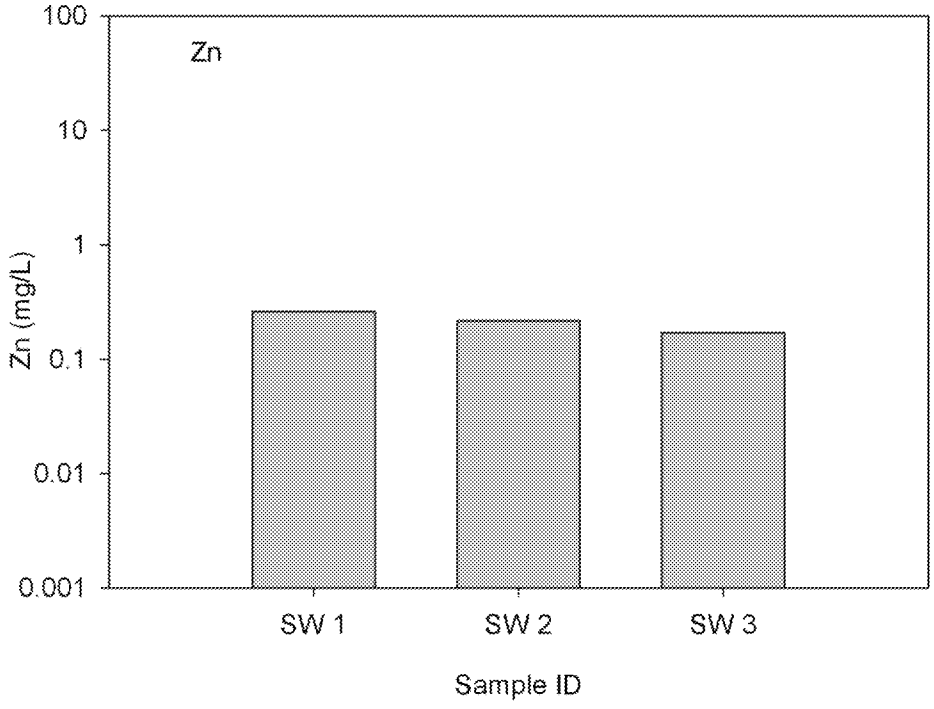


Figure 4-20. Strontium (Sr) and Zinc (Zn) concentrations of PG samples (south wall) in EPTOX test

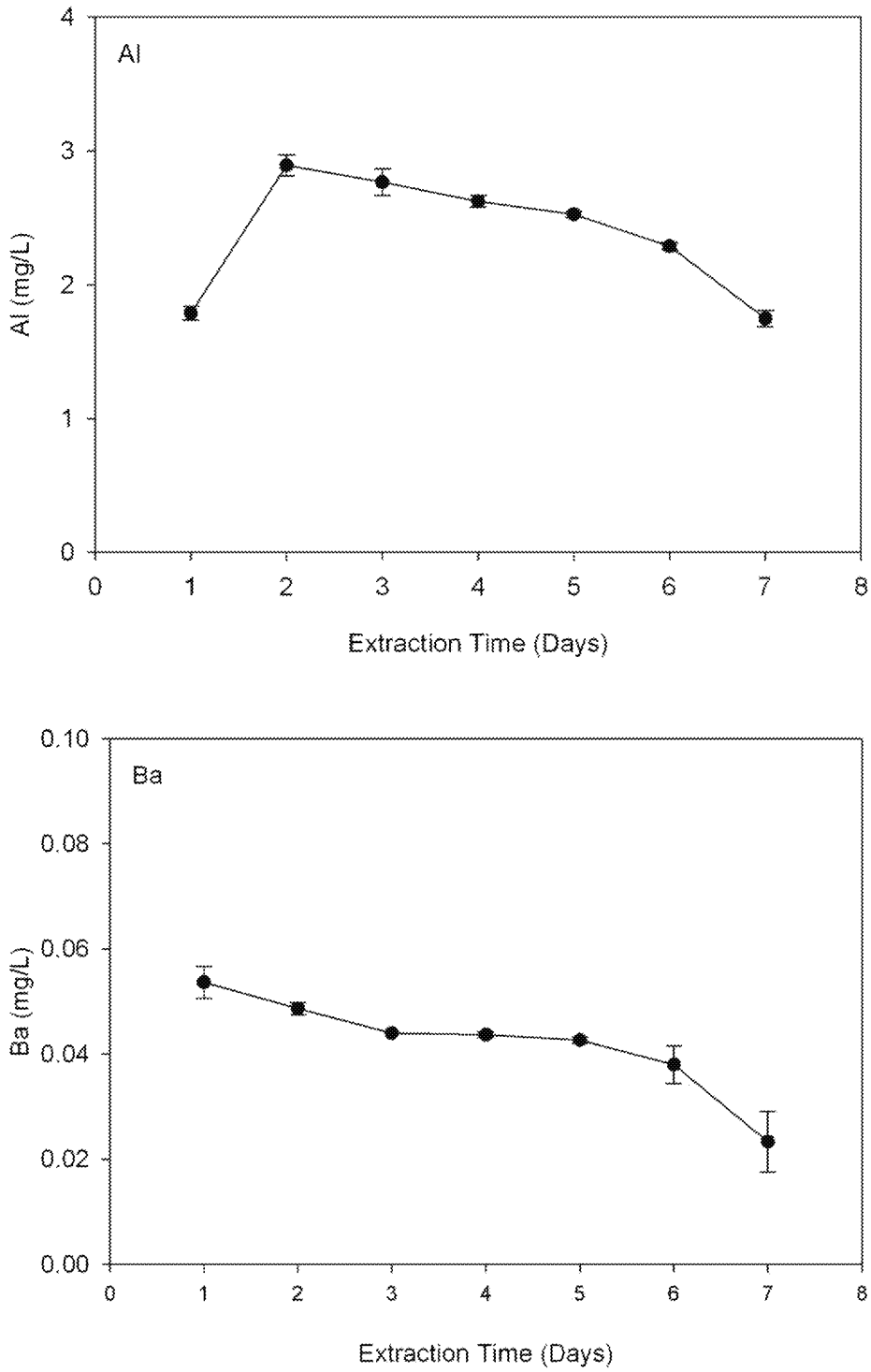
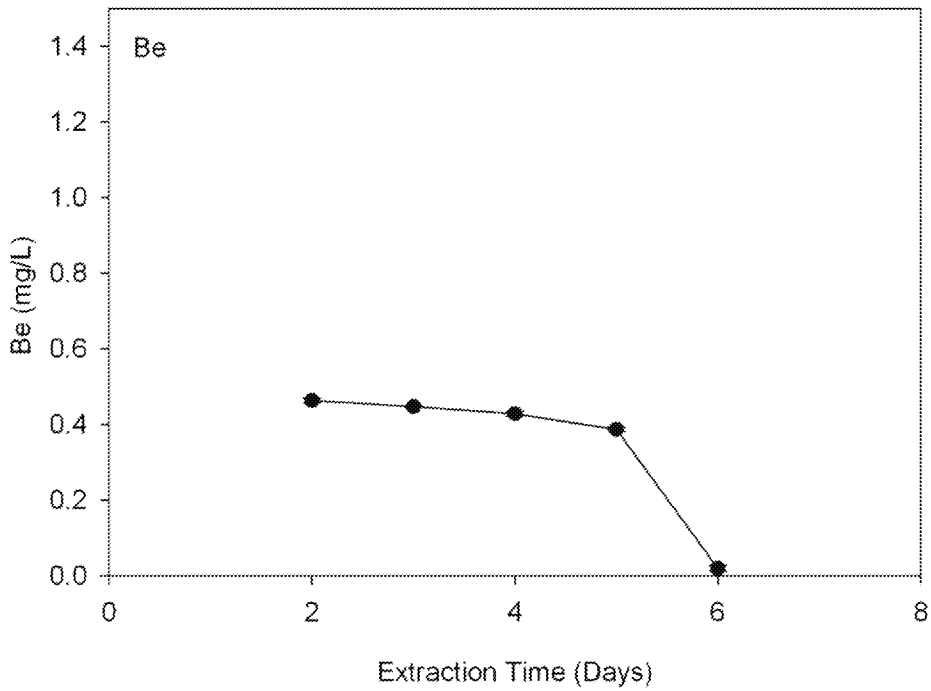


Figure 4-21. Aluminum (Al) and Barium (Ba) leachability in US EPA's MEP



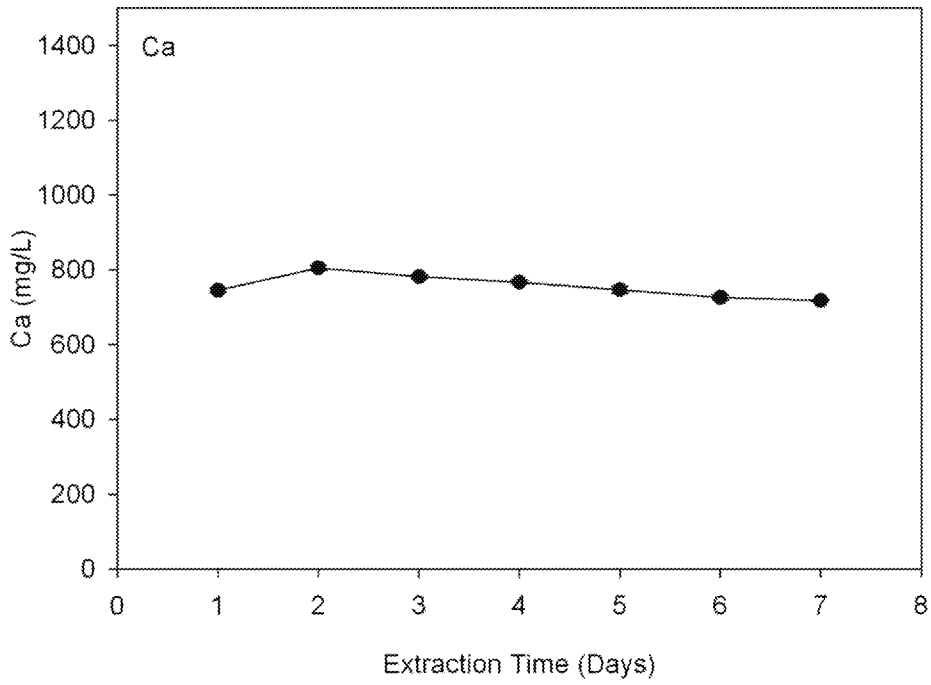


Figure 4-22. Beryllium (Be) and Calcium (Ca) leachability in US EPA's MEP

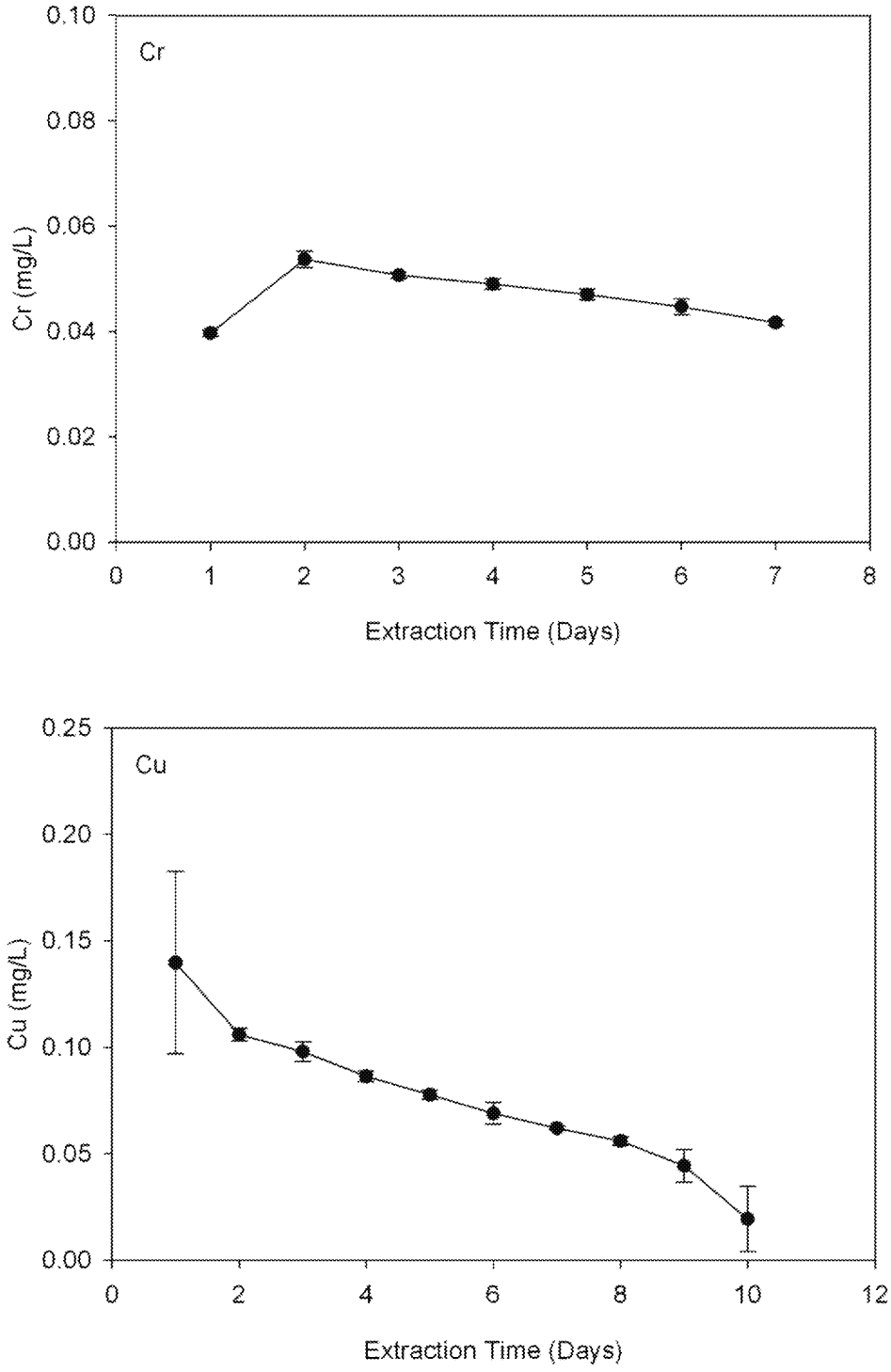


Figure 4-23. Chromium (Cr) and Copper (Cu) leachability in US EPA's MEP

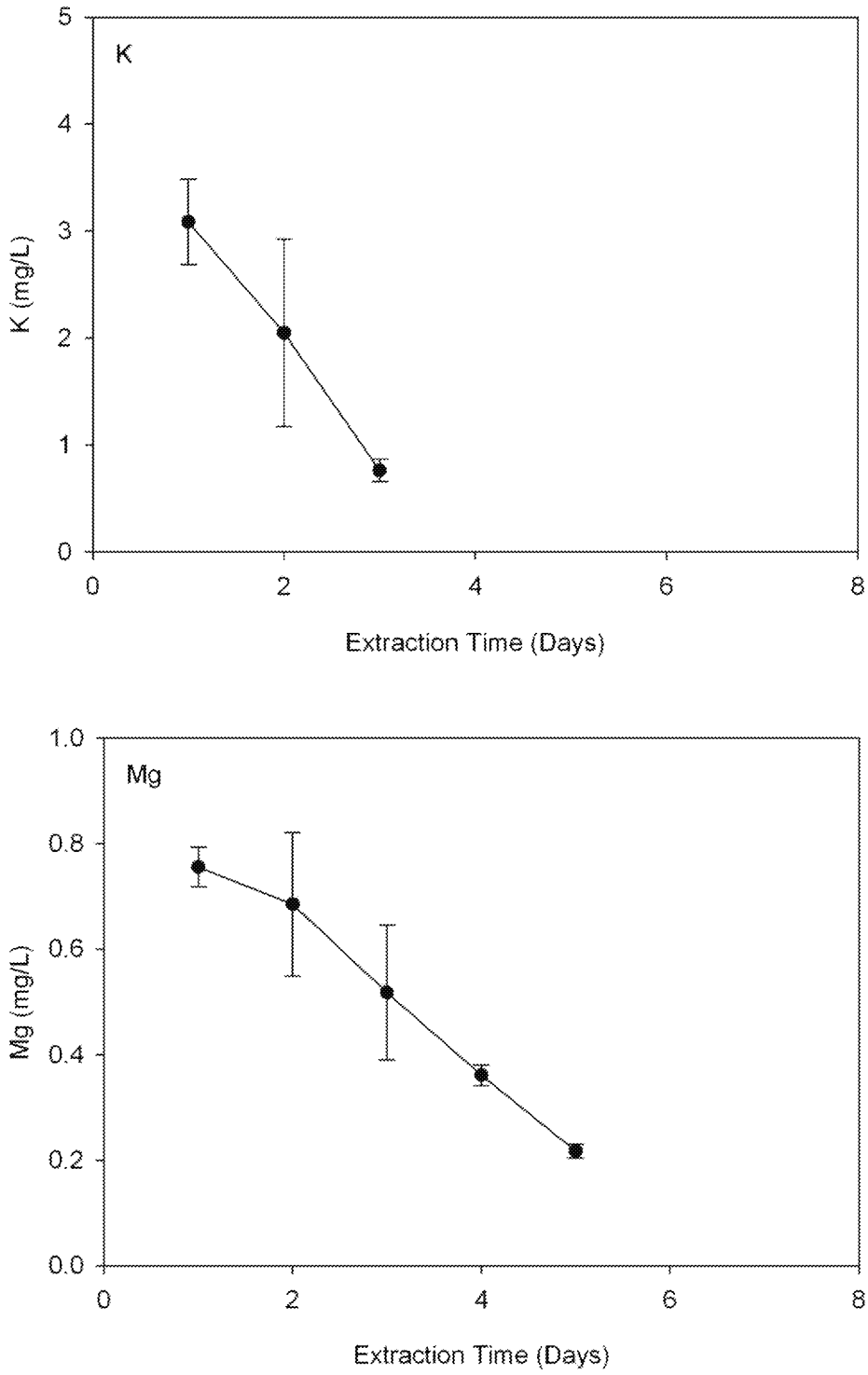
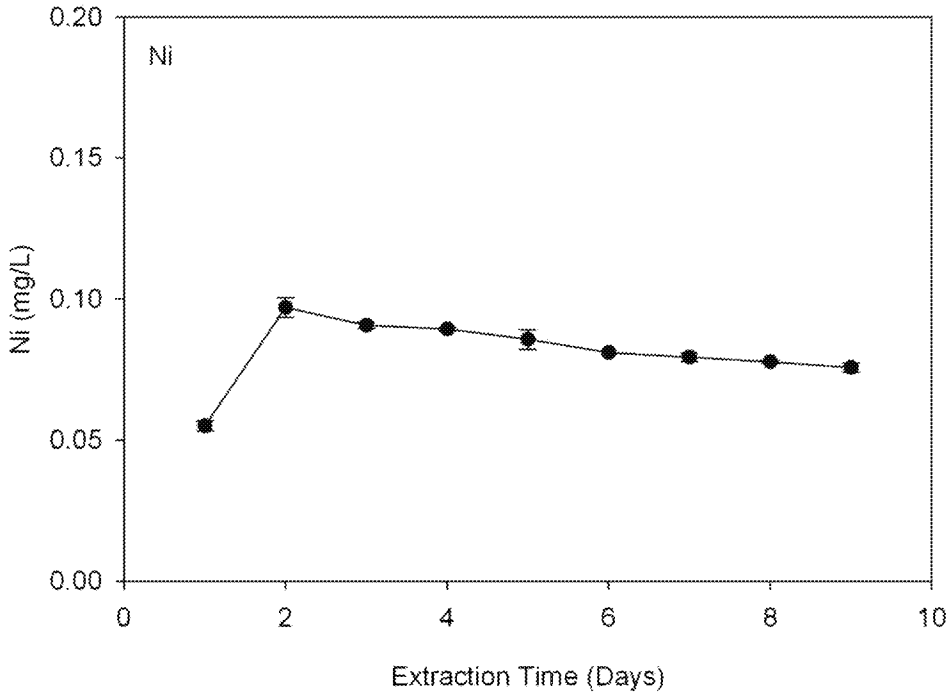


Figure 4-24. Potassium (K) and Magnesium (Mg) leachability in US EPA's MEP



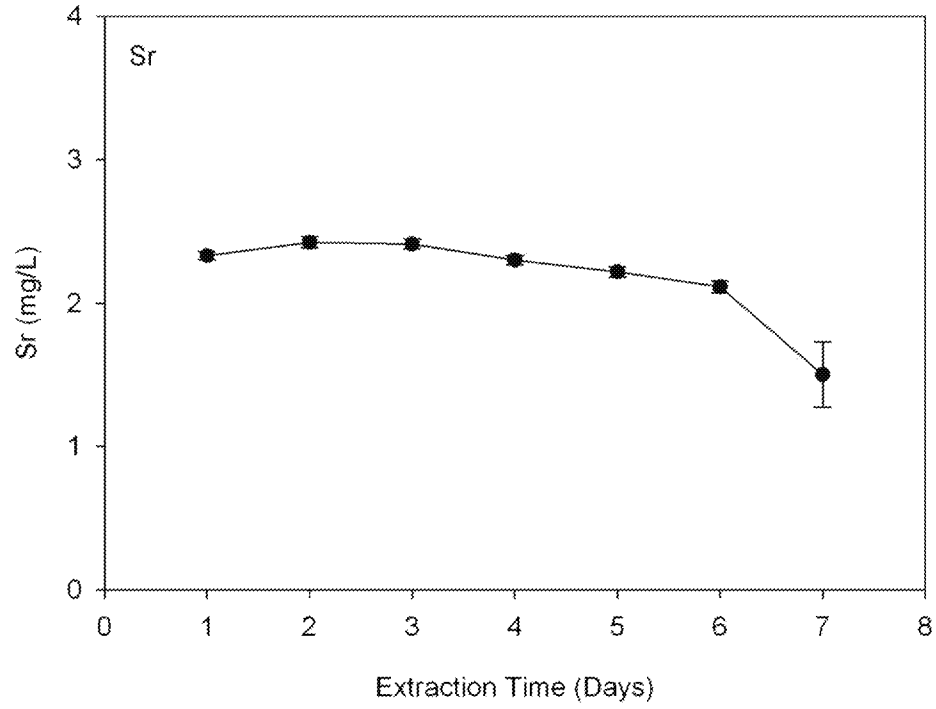


Figure 4-25. Nickel (Ni) and Strontium (Sr) leachability in US EPA's MEP

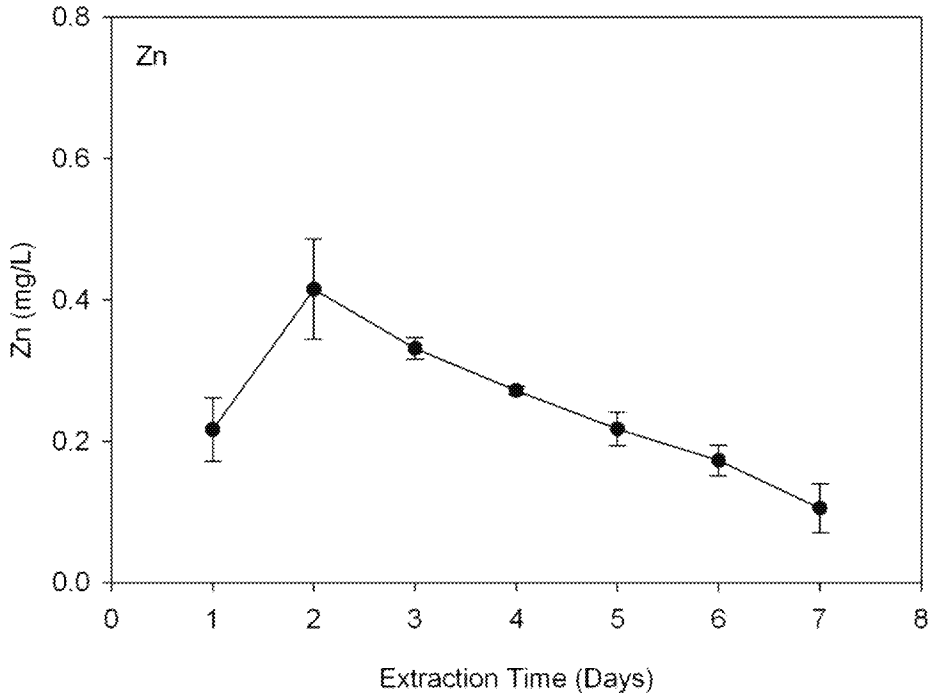
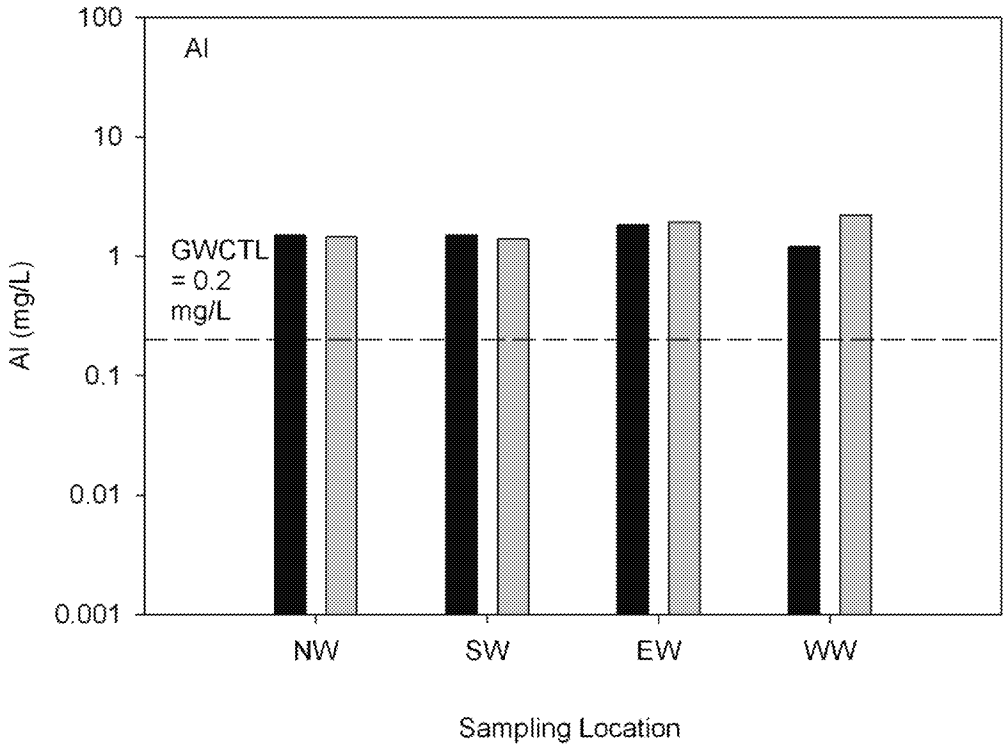


Figure 4-26. Zinc (Zn) leachability in US EPA's MEP



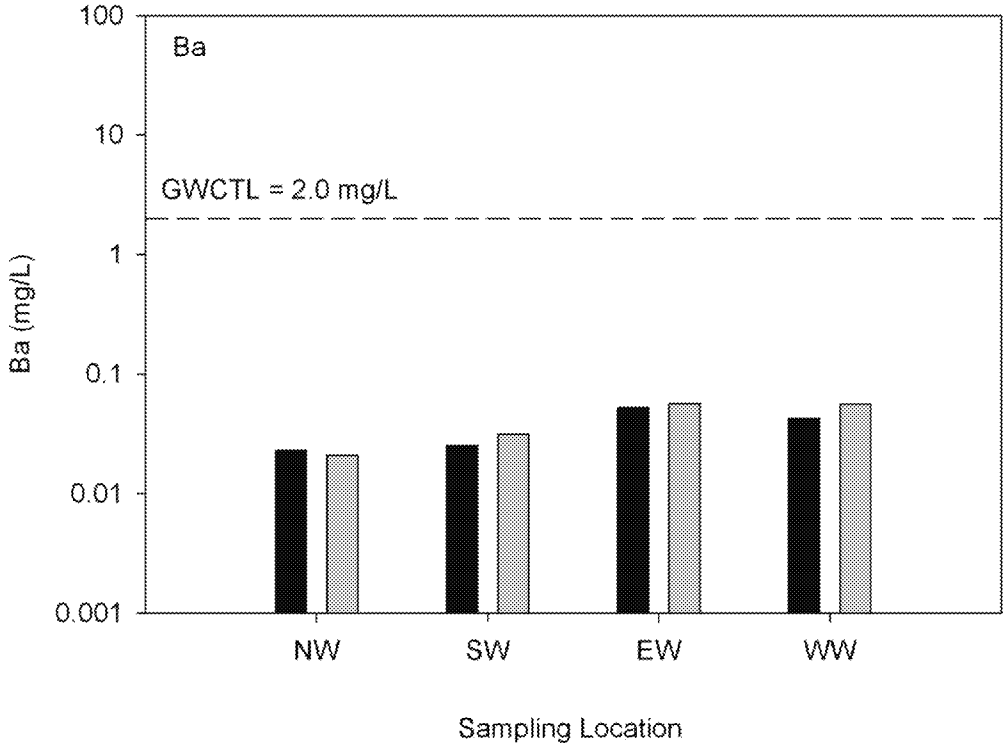


Figure 4-27. Aluminum (Al) and Barium (Ba) concentrations in DI water batch leaching test

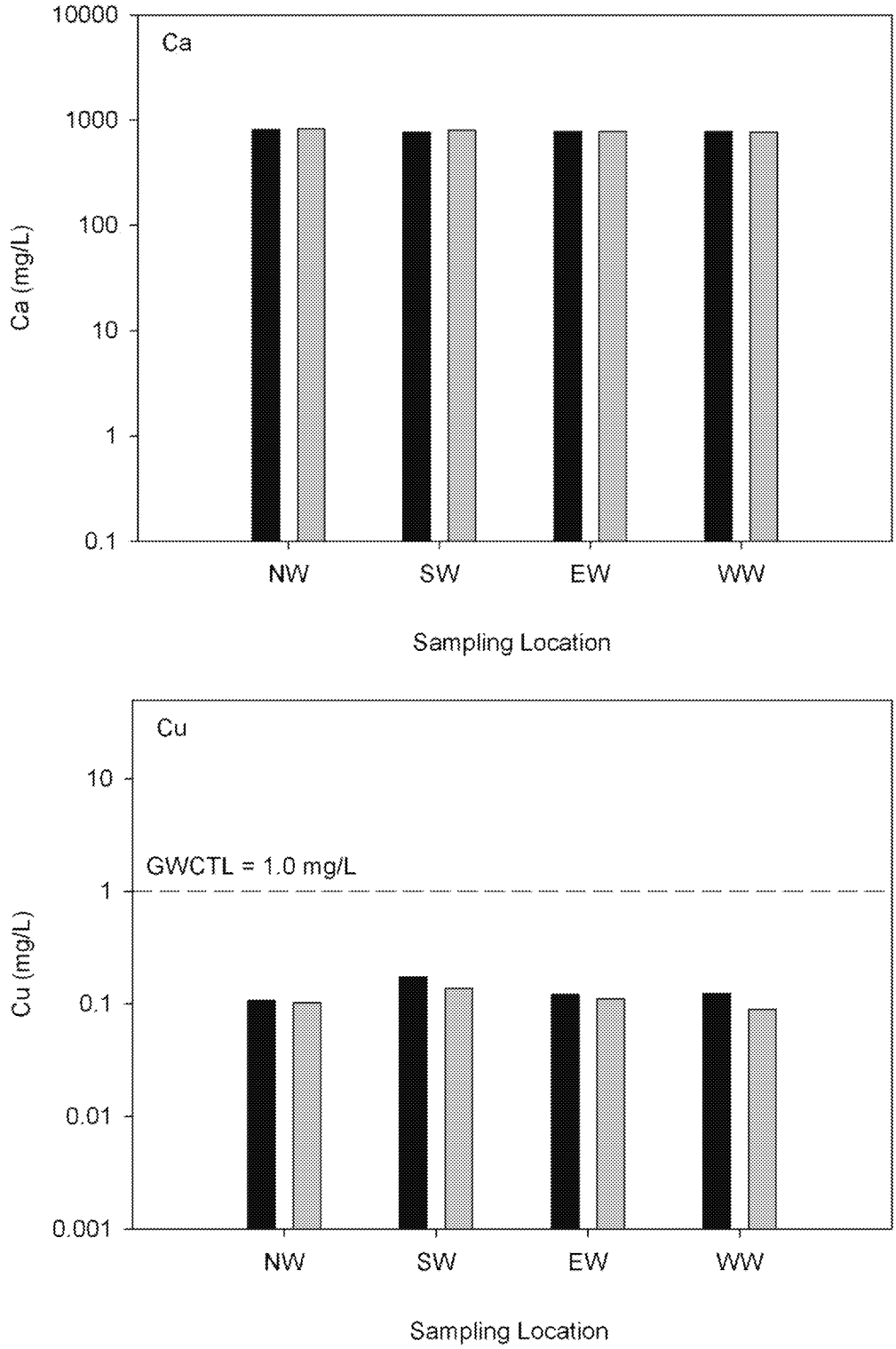
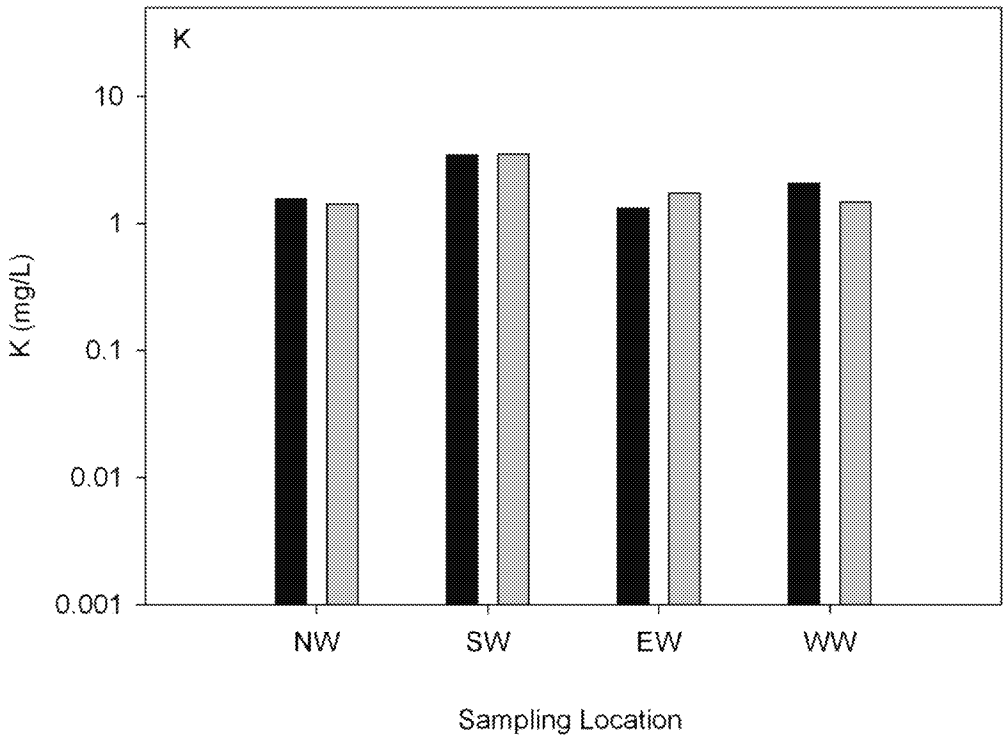


Figure 4-28. Calcium (Ca) and Copper (Cu) concentrations in DI water batch leaching test



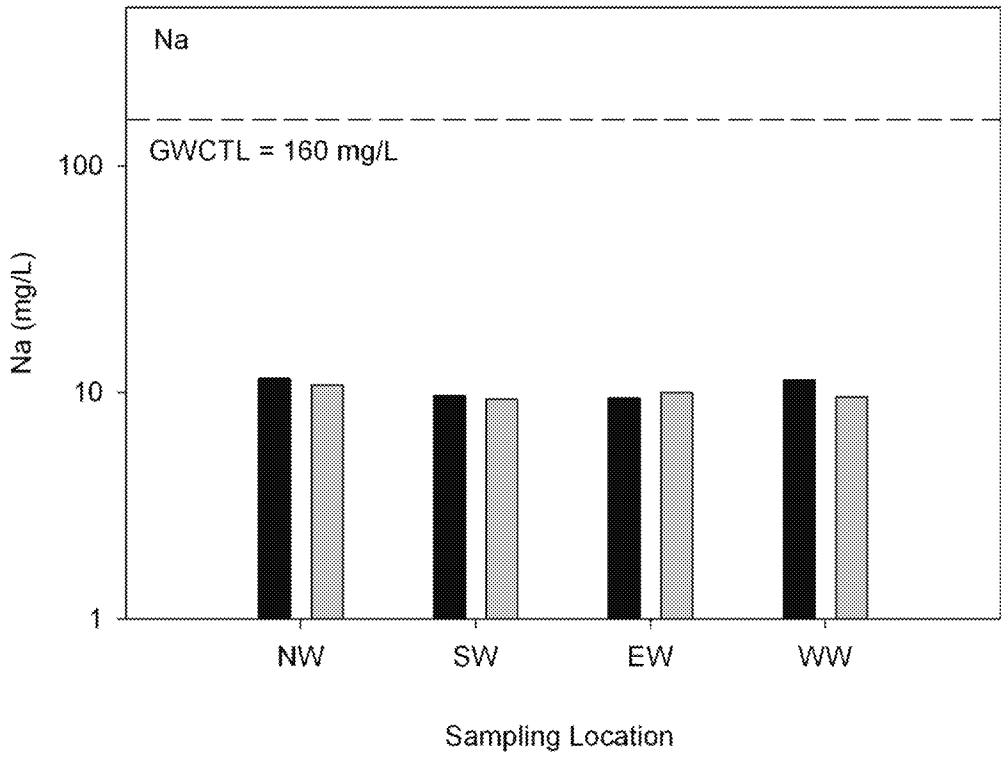
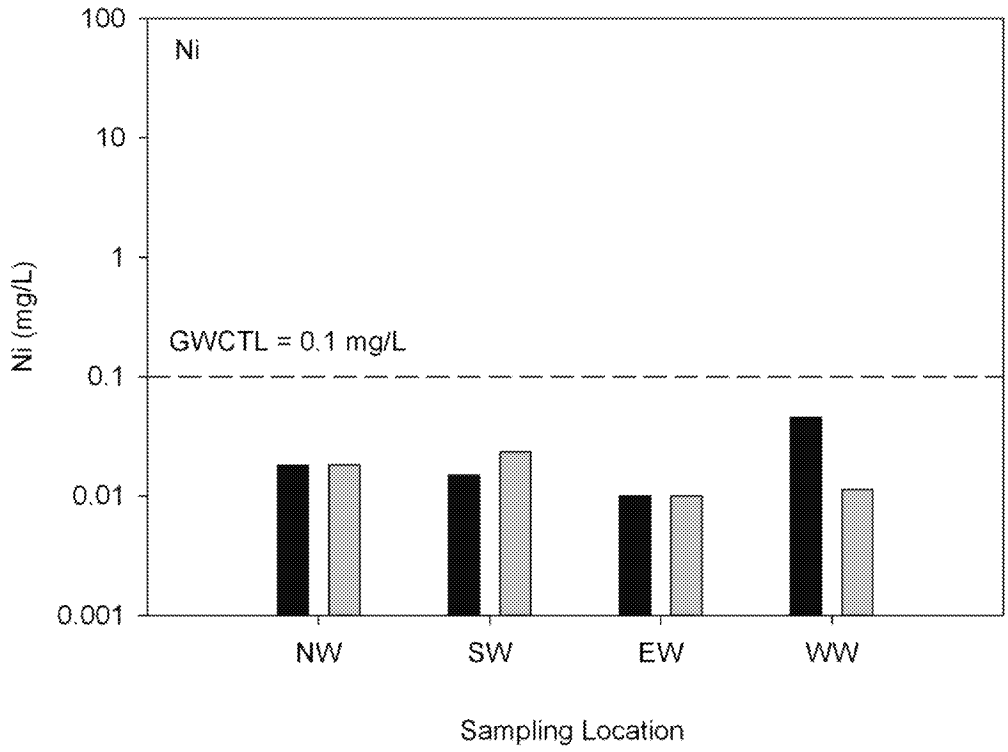


Figure 4-29. Potassium (K) and Sodium (Na) concentrations in DI water batch leaching test



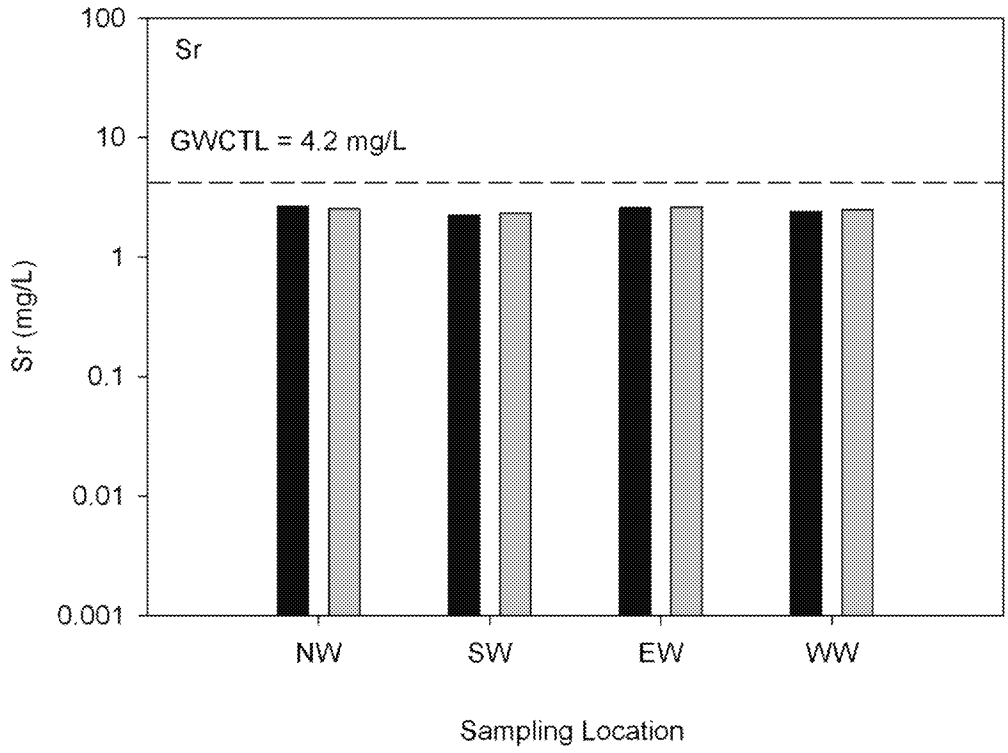


Figure 4-30. Nickel (Ni) and Strontium (Sr) concentrations in DI water batch leaching test

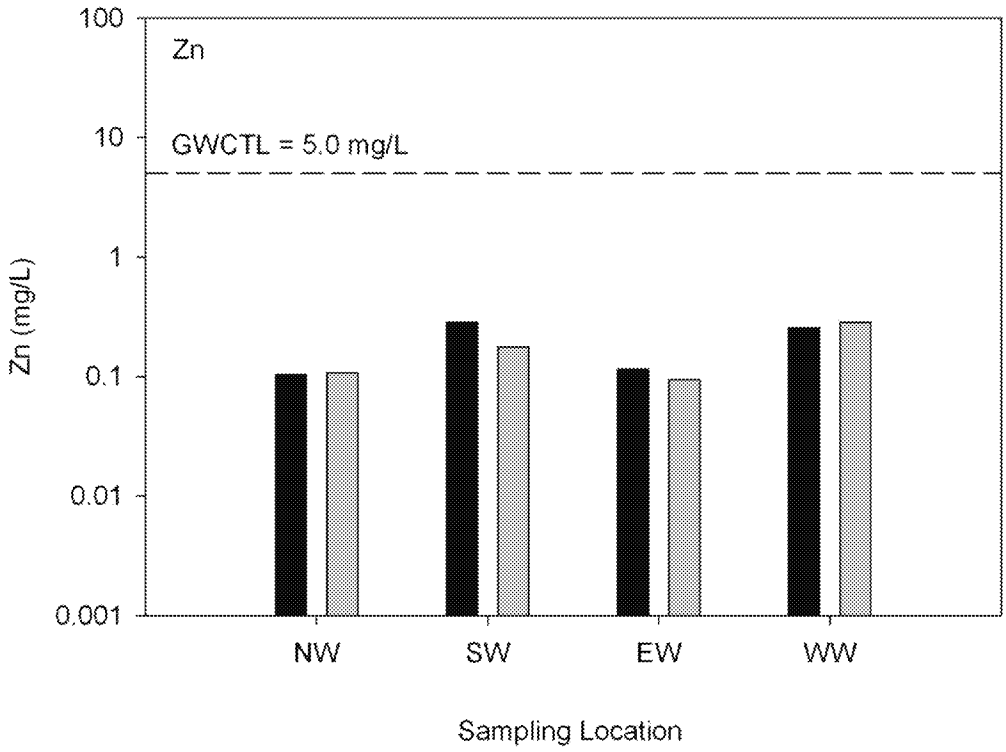
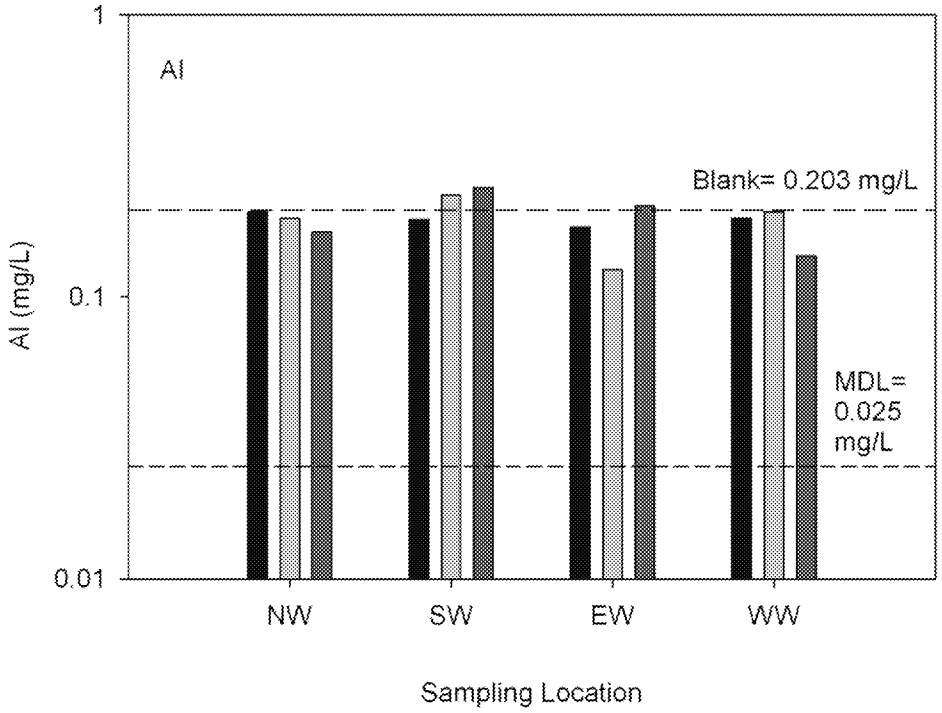


Figure 4-31. Zinc (Zn) concentration in DI water batch leaching test



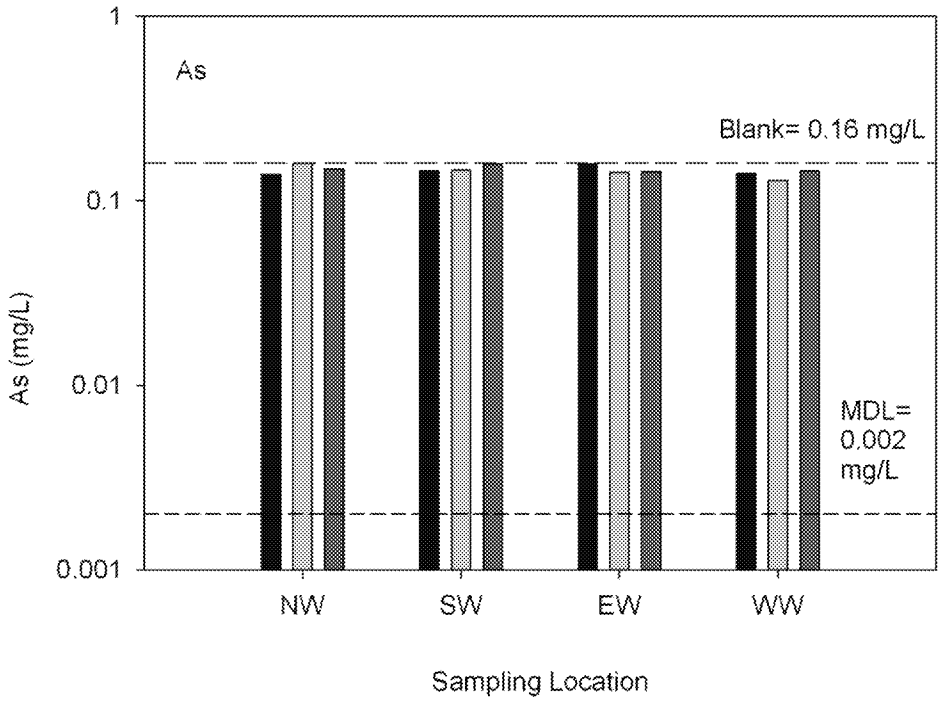


Figure 4-32. Aluminum (Al) and Arsenic (As) concentrations in MSW leachate batch leaching test

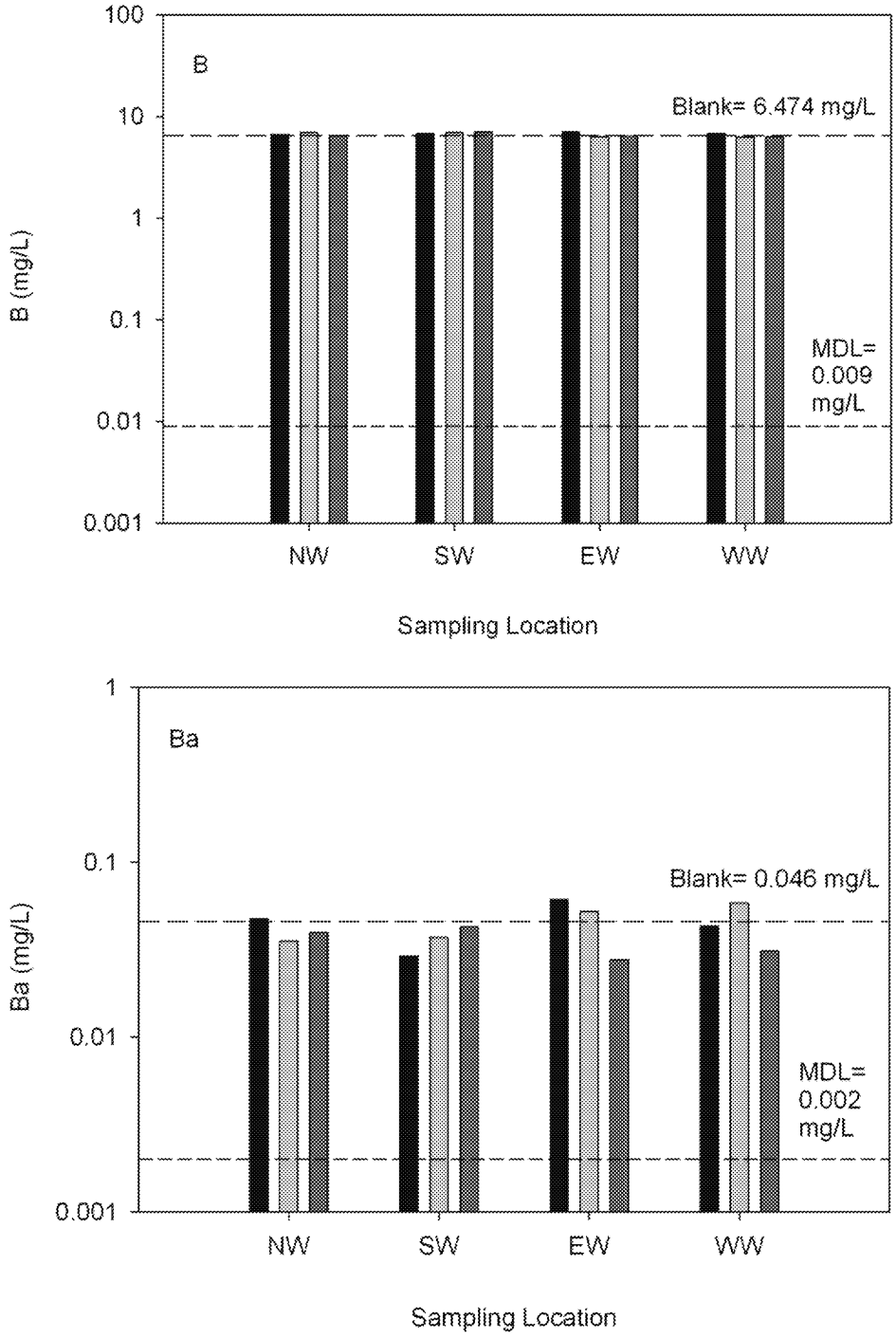
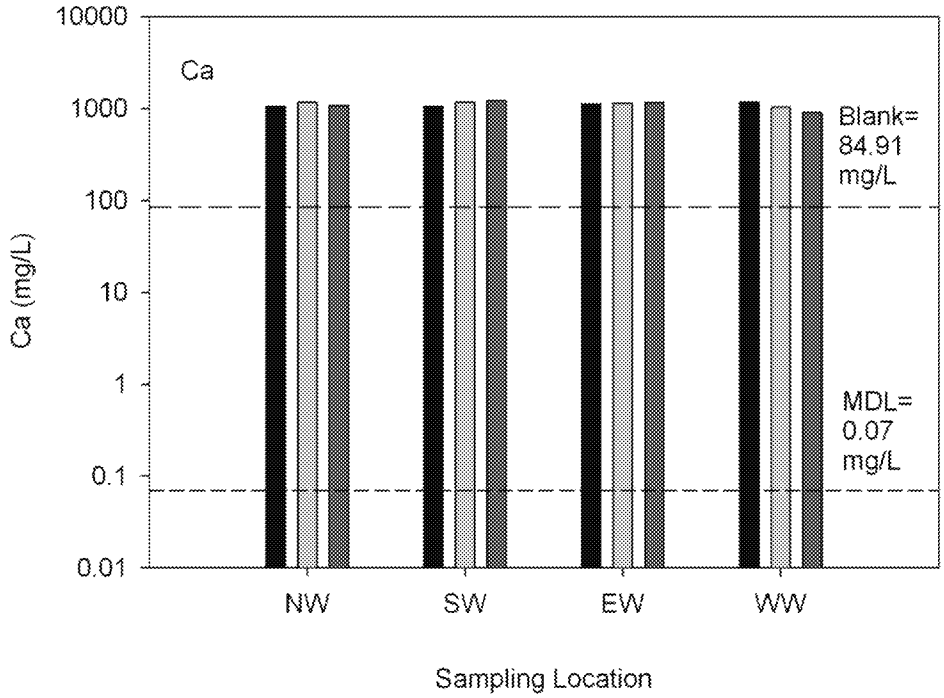


Figure 4-33. Boron (B) and Barium (Ba) concentrations in MSW leachate batch leaching test



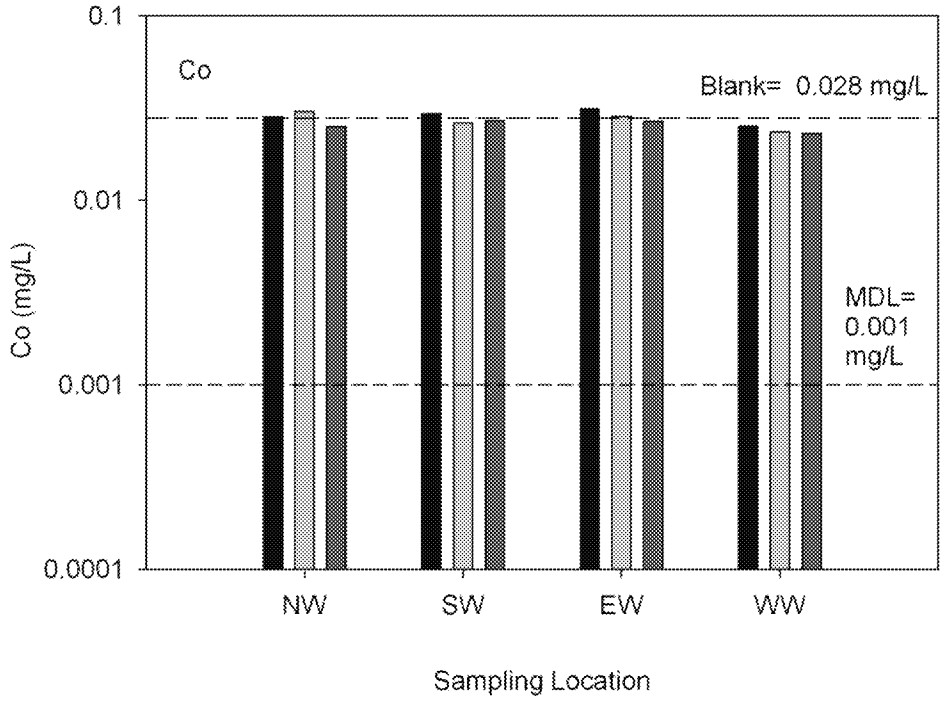
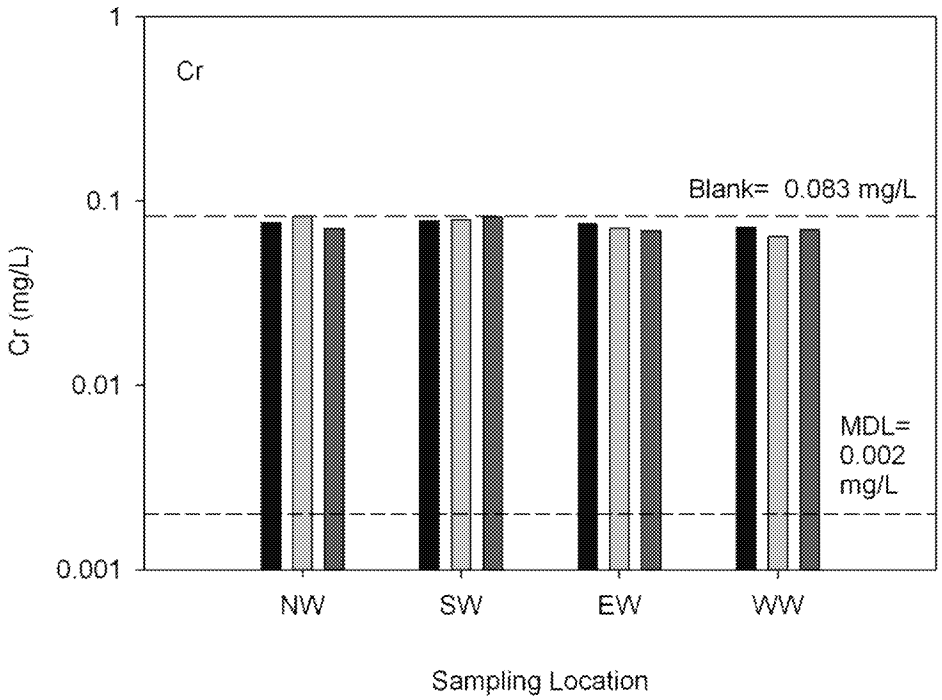


Figure 4-34. Calcium (Ca) and Cobalt (Co) concentrations in MSW leachate batch leaching test



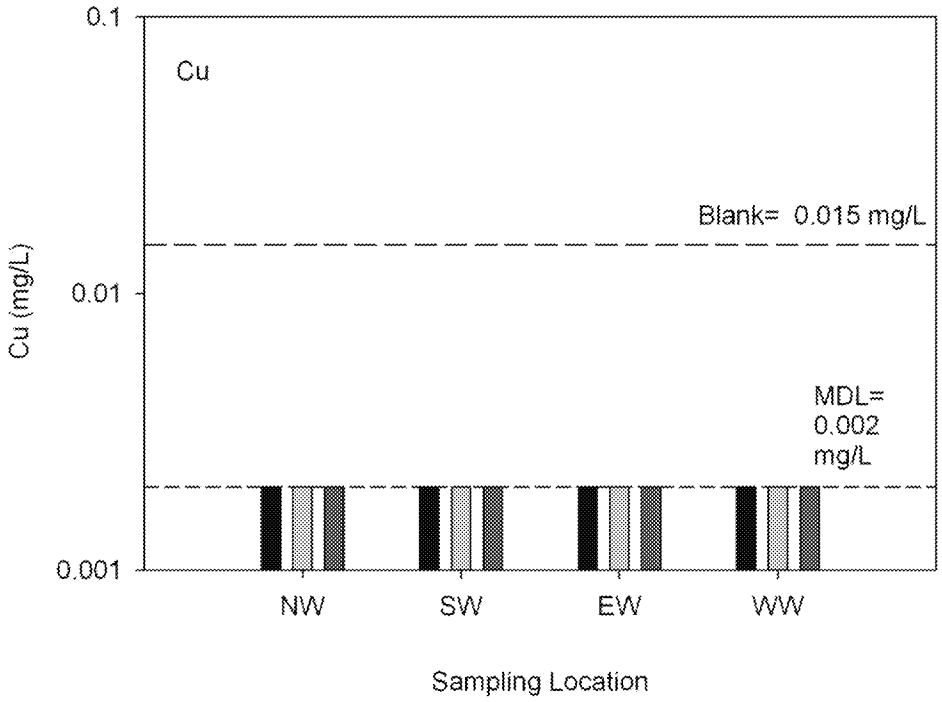
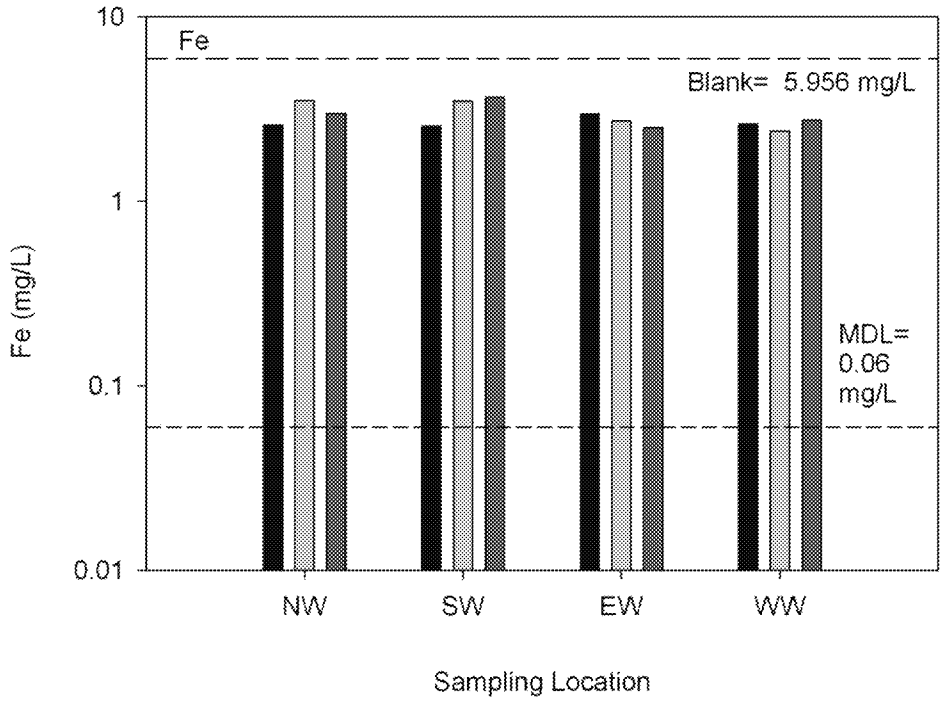


Figure 4-35. Chromium (Cr) and Copper (Cu) concentrations in MSW leachate batch leaching test



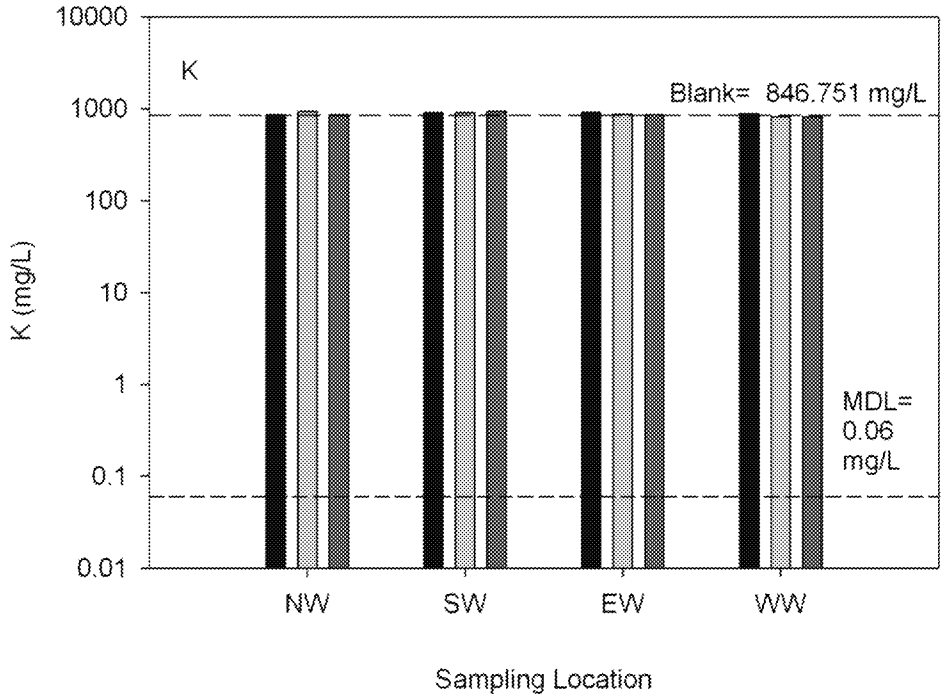
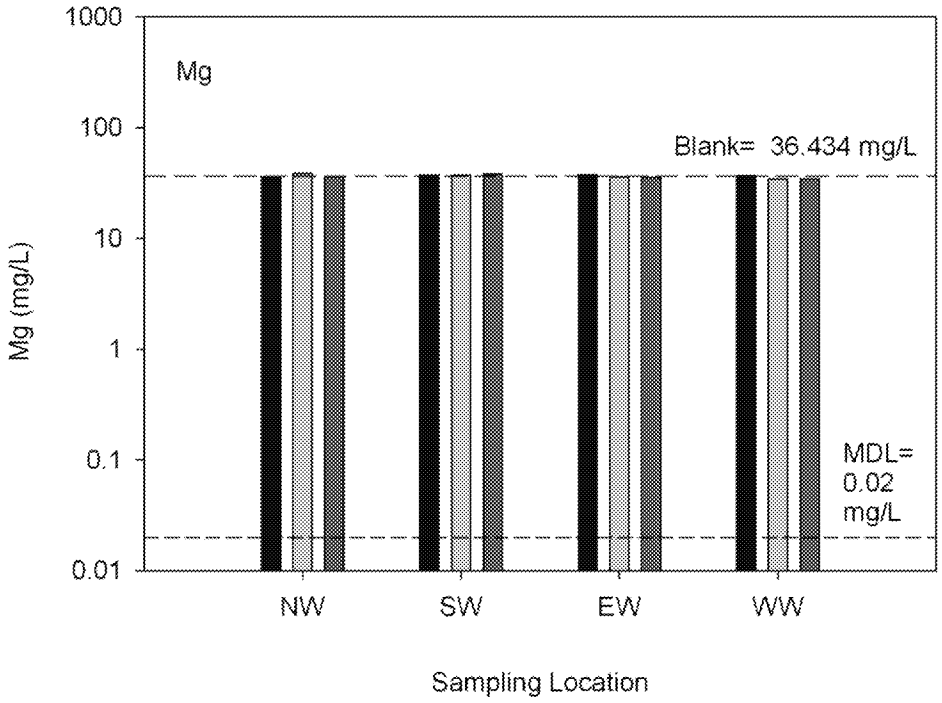


Figure 4-36. Iron (Fe) and Potassium (K) concentrations in MSW leachate batch leaching test



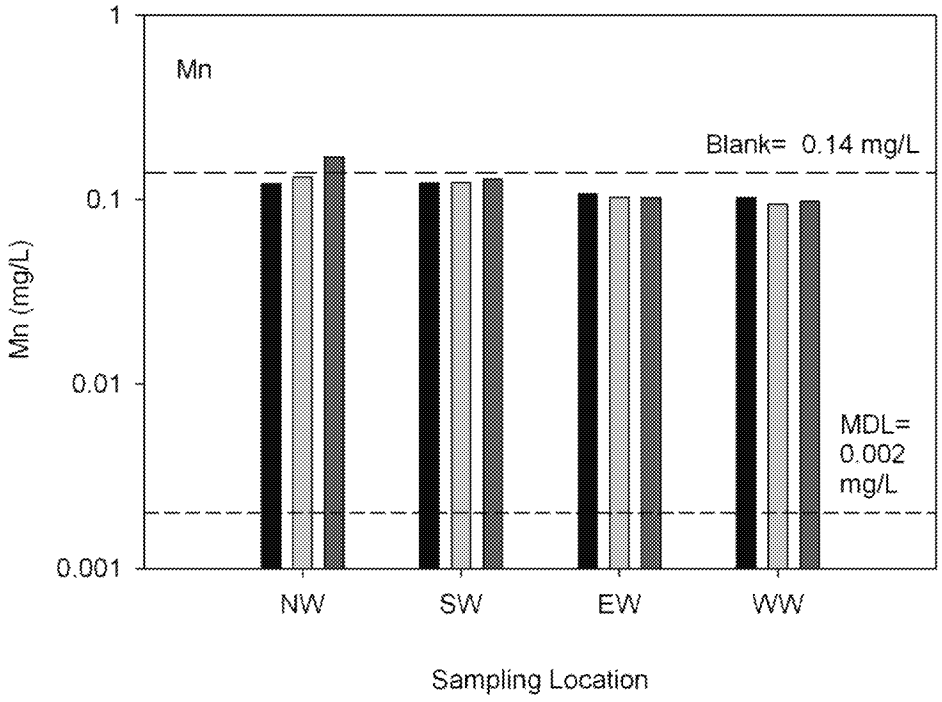
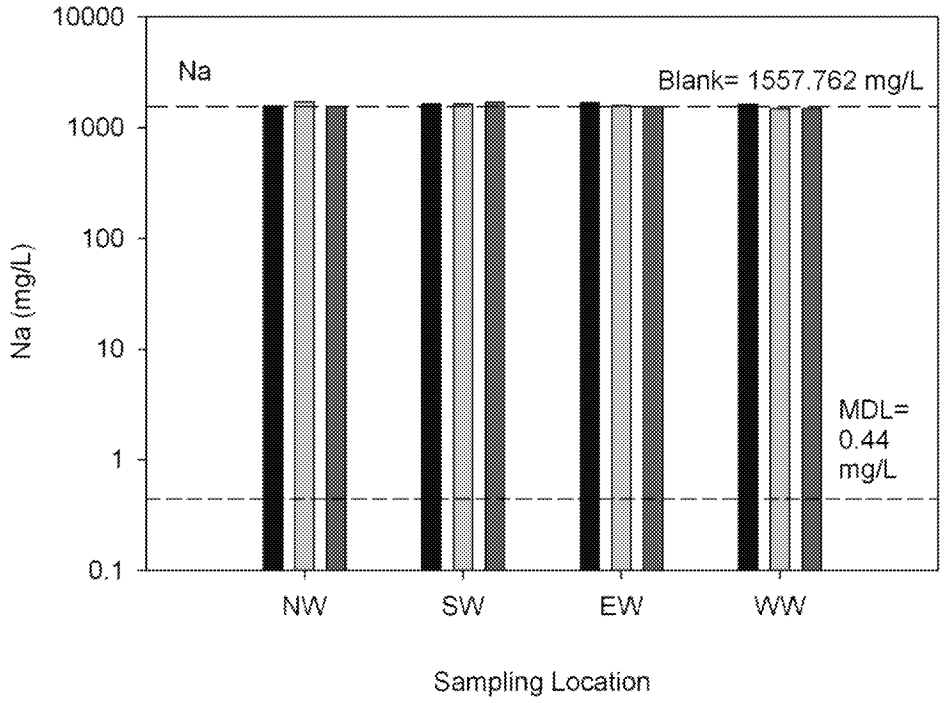


Figure 4-37. Magnesium (Mg) and Manganese (Mn) concentrations in MSW leachate batch leaching test



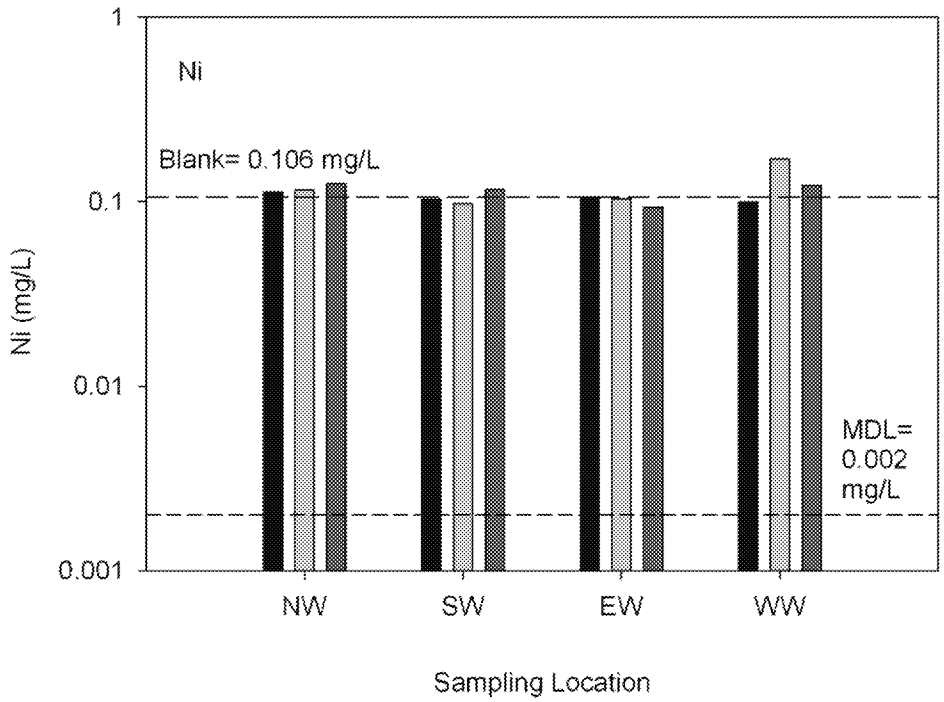
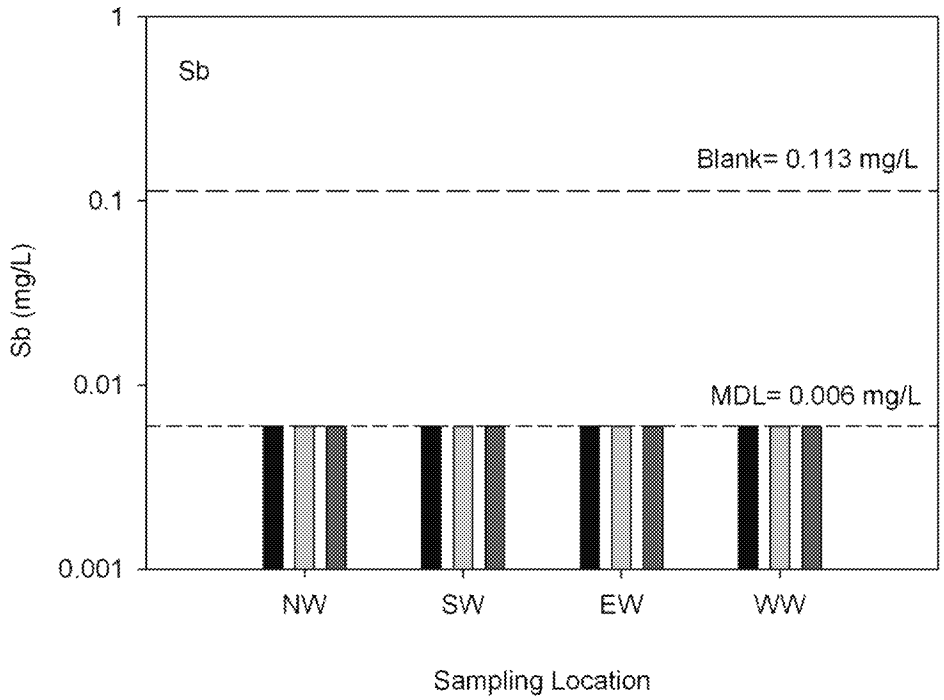


Figure 4-38. Sodium (Na) and Nickel (Ni) concentrations in MSW leachate batch leaching test



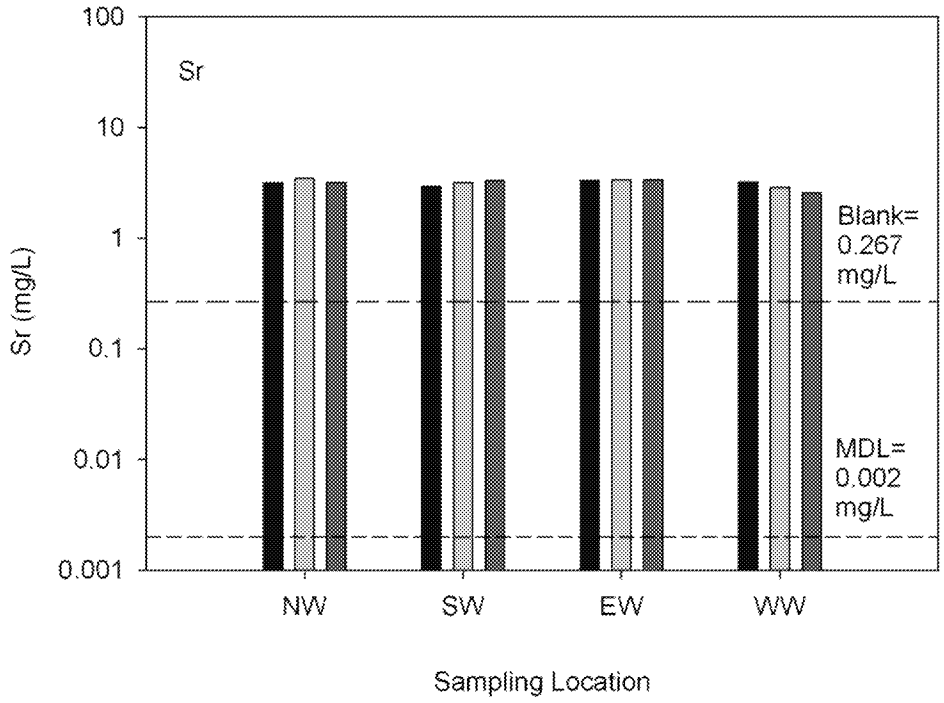
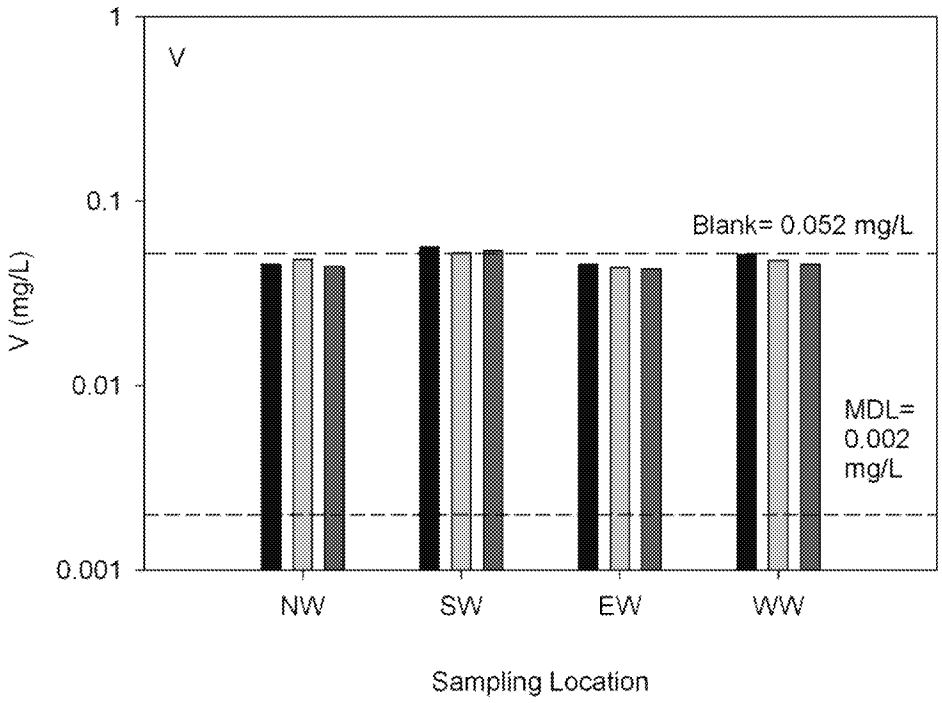


Figure 4-39. Antimony (Sb) and Strontium (Sr) concentrations in MSW leachate batch leaching test



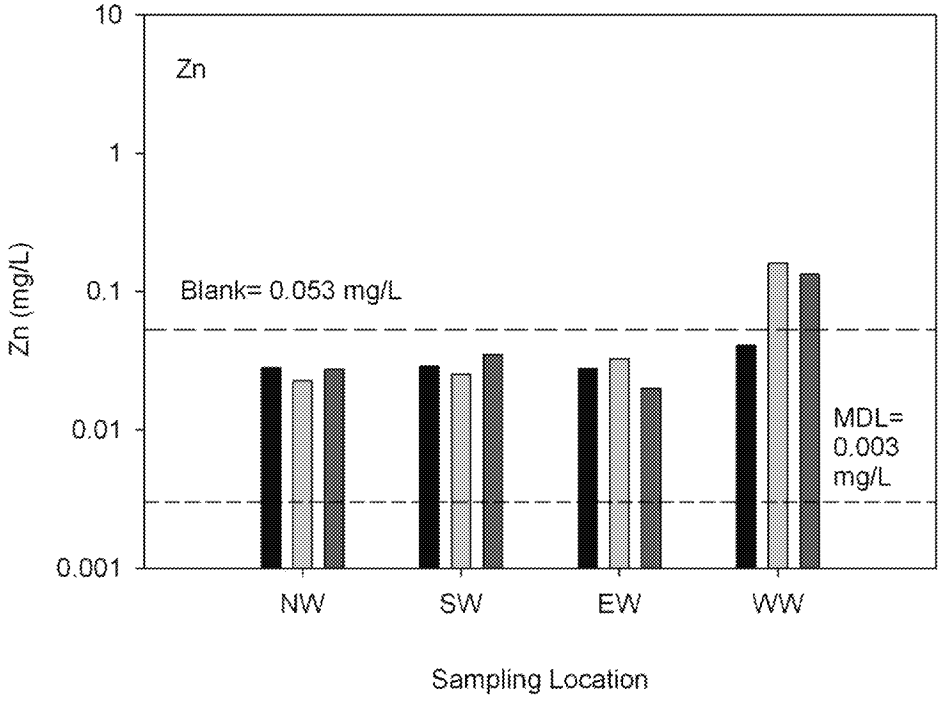


Figure 4-40. Vanadium (V) and Zinc (Zn) concentrations in MSW leachate batch leaching test

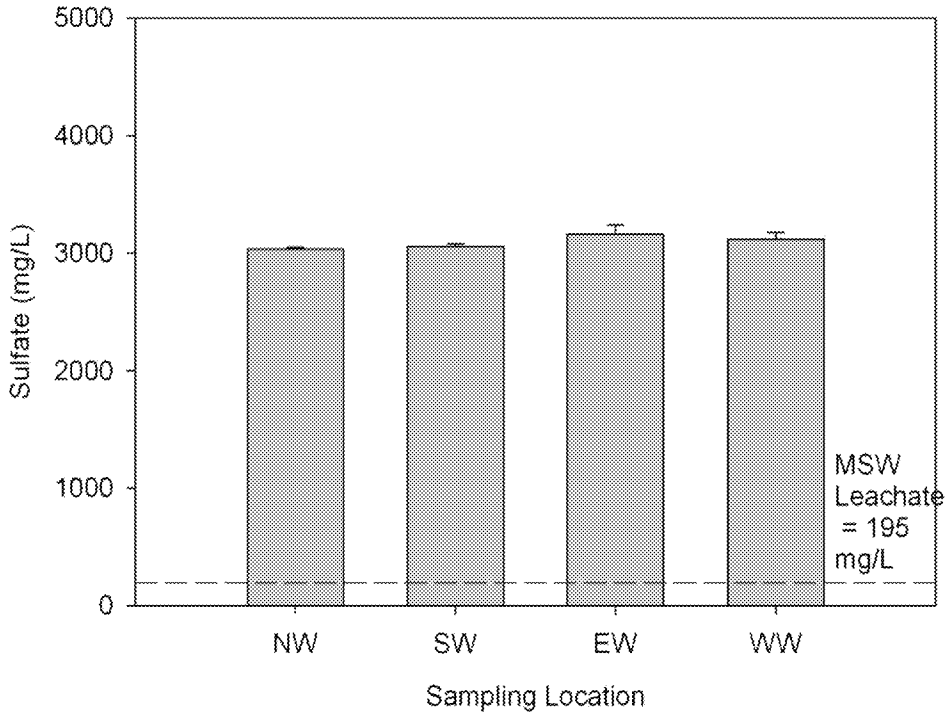


Figure 4-41. Sulfate concentration results of batch test with MSW leachate

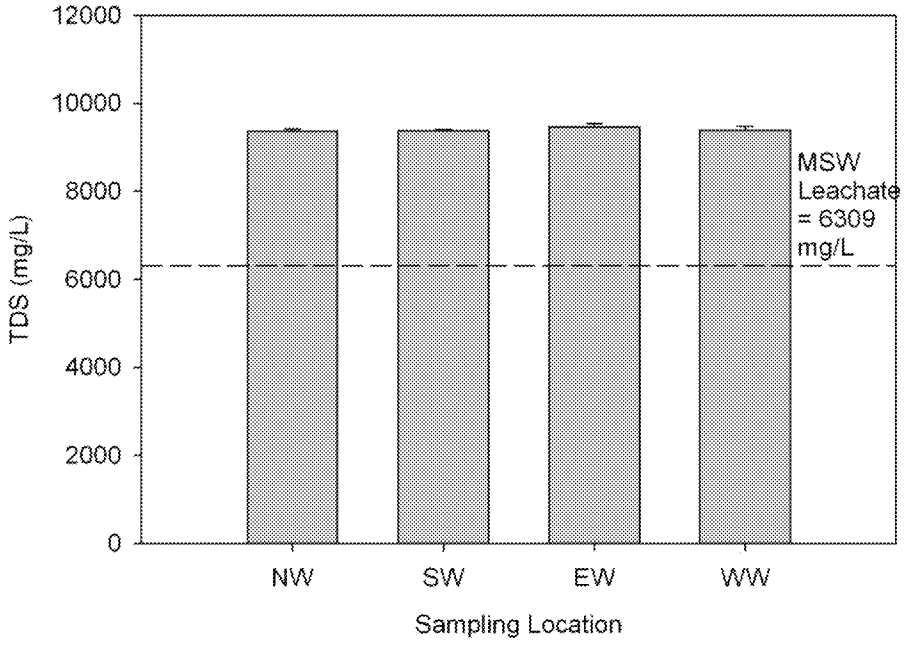


Figure 4-42. TDS results of batch test with MSW leachate

CHAPTER 5
DISCUSSION

5.1 Comparison to Previous Studies

TCLP results found in the previous studies are presented in Table 5-1. In the present study only barium and chromium were detected above detection limits in TCLP, and both were below their respective TC limits. Concentrations of these toxic metals were found below their TC limits in previous studies as well. Mercury was not analyzed in this study; Kendron (1996) reported mercury concentration in TCLP leaching solution from PG below its toxicity limit.

Al Masri et al. (2004) conducted leaching of PG (Syrian) using DI water as a first step of sequential leaching test. In their study they used 1 g PG and 100ml DI water for leaching (L/S ratio of 100:1). The results of the current DI water leaching test are compared with the results obtained in the 2004 study for Cd, Zn and U in Table 5-2.Though Cd was not detected in this study, Zn was leached at a much higher concentration than the previous study. This may be due to the high L/S ratio (20:1) used for this study. The bioavailability and mobility of trace metals (As, Cd, Cr, Cu, U, Zn) were estimated by Al-Hwaiti et al. (2010) using aqua regia leaching solution. Results are presented in Table 5-3.They used 50 mg of dried PG and 5 ml of nitric acid and hydrochloric acid (aqua regia) and rotated for 48 hours. All the metals tested leached below 10% (fraction leached) but the concentrations of all the metals were above detection limits. In comparison to that study, SPLP performed in this study leached a higher percentage of Cr, Cu and Zn.

Metal concentrations of PG is compared with gypsum wallboard in Table 5-4 Relative to gypsum wallboard, PG was elevated in total content of Al, As, Ba and K.

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5.2 Discussion of Leaching Results

Arsenic was detected above SCTL in total metal analysis. But it was not detected in any of the leaching tests. When metal concentrations extracted by the SPLP are compared to those of the TCLP, calcium was leached to a greater extent in the TCLP than in the SPLP; silver, arsenic, boron, cadmium, cobalt, magnesium, lead, antimony, tin and vanadium were not detected in either test. Barium, chromium, iron and strontium concentrations in the TCLP leachate were higher than the SPLP leachate, but relatively similar. Only sodium was dramatically greater in the TCLP compared to the SPLP, but this was because sodium is used in the TCLP solution. The TCLP and SPLP extracted statistically similar concentrations of aluminum, copper, potassium, nickel and zinc. Comparisons of TCLP and SPLP for other wastes have found that TCLP typically extracts more metals than SPLP because of the buffered pH of the TCLP and the ability of acetic acid to complex heavy metals. The degree of complexation differs depending on the metal. Differences in metal leachability between TCLP and SPLP could be result from several other factors. The initial pH of the SPLP solution (4.2) is less than the initial pH of the TCLP solution (4.9). Also changes in the solution pH that occur during the 18 hour of leaching may differ between SPLP and TCLP, and thus result in different amounts of metal leaching. In the case of PG, the pH difference between the two tests was not very pronounced. The difference in metal concentrations between SPLP and TCLP for PG are relatively small.

Figures 5-1 through 5-4 compare the average leachate concentrations using SPLP, TCLP, DI and EPTOX for aluminum, barium, chromium and calcium. For aluminum, all the tests leached similar concentrations and all of them were above GWCTL. Barium was below TC limit for all the tests and TCLP leached barium greater

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than SPLP and EPTOX. While MSW leaching solution leached calcium more than TCLP, EPTOX and DI showed similar concentrations of calcium.

When the PG samples were leached with DI water, extracted concentrations were relatively similar to the SPLP except calcium. DI water leached more calcium than SPLP. The pH of DI water used for this test was greater than the TCLP and SPLP extraction solutions. The pH is known as a major controlling factor for metal leachability (Van der Sloot et al. 2001; Townsend, et al. 2004). The solubility of some metals increased under extreme pH but this may not be applicable for all. For some metals the change in pH had no effect (Tolaymat et al. 2008; Chuan et al. 1996). For some wastes like wood, tire ash and wood ash, calcium, potassium and sodium concentrations were controlled by solubility rather than pH (Tolaymat et al. 2008).This may be the case for PG also.

The fact that most of the metals (except calcium) leached less in the MSW landfill leachate relative to TCLP and SPLP is likely a result of the higher pH. Average pH of leaching solution after 18 hours of agitation was 7.5 and initial pH of MSW leachate was 7.7 (Table 4-7). MSW leachate also leached considerable amount of sulfate from PG. Under anaerobic landfill conditions, sulfate-reducing bacteria produce hydrogen sulfide (H_2S) from the sulfate (SO_4^{-2}) in gypsum and the organic carbon in waste material: $SO_4^{-2} + 2CH_2O \text{ ---> } 2HCO_3^{-1} + H_2S$.

Here a simple hydrocarbon is used as a surrogate for organic wastes. This may cause odor issues and possible health problems for workers.

For MEP some metals showed an increase in concentration in the second extraction from the first extraction. As a reminder, the first extraction of the MEP was

performed using EPTOX extraction fluid (at a pH of 5.0). The subsequent extractions were performed using a pH 3 synthetic rainwater solution. After first extraction, average pH of leaching solutions was 4.71 (after 20:1 dilution) and after second extraction, the pH decreased to 3.39. Studies have demonstrated that as pH decreases, metal desorption increases; thus, metals are more soluble under acidic conditions, which could be attributed to the tendency of metals to form soluble metal oxides in acidic environments. After second extraction metal concentrations decreased with subsequent extractions as there are less contaminant available for leaching.

5.3 Assessing Potential for Beneficial Reuse

The research presented here provides helpful information for making preliminary assessments for phosphogypsum uses. Of all the trace elements analyzed in total metal analysis test, only arsenic (UCL_{95}) was found to exceed its respective SCTL value (residential exposure). Following typical risk assessment procedures for the state of Florida, this suggests that PG cannot be land applied in a setting where direct human exposure might occur. When the SCTLs are utilized to assess risk from land application of a waste, the waste materials are assumed to be present in a manner where they replace the soil. In the case of an amendment such as PG, the waste is mixed with soil and the concentration of chemicals that an individual is exposed to is not only a function of the PG composition, but also of the background soil concentration and the rate of application (Tolaymat et al. 2008). Also PG can be used in conjunction with other materials such as coal ash for soil amendment (Lee et al. 2008). Further study with mixed materials may explore beneficial use options. One important factor in the use of phosphogypsum on agricultural lands is the possibility of radioactive element uptake by plants. Mays and Mortvedt (1986) applied phosphogypsum containing 25 pCi g^{-1} ^{226}Ra

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at rates up to 112 Mg ha^{-1} to the surface of a silt loam soil and grew successive crops of corn, wheat, and soybean. Application of phosphogypsum at a rate of 112 Mg ha^{-1} had no effect on the radioactivity levels in grain of corn, wheat, or soybeans. Analyses of soil after soybean harvest showed that the level of radioactivity in the surface 15-cm layer increased from 35 Bq kg^{-1} to 73 Bq kg^{-1}at 112Mg ha^{-1} PG rate; the radioactivity level in the subsurface layer was not affected. The 112 Mg ha^{-1} rate was more than 200 times the normal rate of gypsum used for peanut fertilization. Additionally, they noted no increases in grain Cd levels, but at the highest rate they found that corn growth slowed. They speculated that the slower growth was due to an imbalance of Ca and Mg.

PG leached Al and Fe above GWCTL in SPLP, therefore cannot be reused in Florida for land application, however, Al and Fe are secondary standards, and the other leaching tests showed low leachability of heavy metals, so beneficial use possibilities may exist under different regulatory scenarios. In fact PG can be used to alleviate Al toxicity(In soil solutions containing abundant SO_4^{2-} and F^-, Al that is not complexed with either of the ligands) from acid soil due to its precipitation and complexation reactions with SO_4^{2-} and F^-. The reduction of Al toxicity in the subsoil by PG is a result of complex set of mechanisms, including precipitation of aluminum as the result of liberation of OH^- ions from oxidic surfaces by ligand exchange with SO_4^{2-}, formation of insoluble basic Al sulfates, formation of complexes of Al with F (AlF^{2+}, AlF^+_2 and AlF_3).which are less toxic than the uncomplexed forms of Al (Carvalho and Raij 1997, Alva and Sumner 1991).

From the leaching tests (TCLP, EPTOX, MSW leaching) it can be said that none of the toxic metals that were tested in this study leached above TC limits. One potential beneficial use of PG is its utilization as part of MSW landfill construction and

maintenance activities. Other possibilities are using PG as daily and intermediate landfill cover and landfill foundation. At new landfill sites, compacted PG may be used as a substitute for the large volume of soil required to be placed under the liner to provide necessary grades. When MSW leachate contacts with PG, a few constituents of PG such as calcium and sulfate, may be considerably leached out. PG samples released considerable amount of calcium in all the leaching tests. Increased calcium concentration in MSW leachate may enhance scaling in the leachate collection and removal system. Sulfate also was considered as an easily mobile constituent from PG to MSW leachate. Increasing sulfate in MSW leachate may be a concern in terms of odor issues. On the other hand, in an anaerobic environment of landfill, PG could enhance biodegradation of municipal solid waste (MSW) in the landfill. Since PG is enriched with sulfate, it is reasonable to assume that a sulfate using bacterial colony present in landfills will use phosphogypsum as an energy source after oxygen is depleted. So use of phosphogypsum as landfill cover could enhance biological decomposition of MSW.

However, if PG is utilized as a base material under a landfill bottom liner, these issues may not be concerns because the contact of PG with MSW leachate would be prevented by the landfill liner. However use of PG, in applications where it is in contact with the MSW (either as cover material or as a direct amendment), needs to balance the potential benefits (less soil usage, greater stabilization) with the potential deleterious impacts (odors, impact on biogas collection and conversion systems). Exploration of these uses was not the main focus of this study. But results of this study can be used for the feasibility study.

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5.4 Limitations and Recommendations

In this study, leachability characterization of PG was conducted using only batch leaching test. For better understanding of PG leachability, dynamic leaching test and other batch leaching test using different pH solutions and solid liquid ratios could help evaluate how several test variables can affect leaching behavior of PG. Also leachability studies could be conducted on PG along with other materials to see how they affect leachability characteristics of PG.

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Table 5-1. TCLP results found in the previous studies

Element	Regulatory limit (mg/L)	FIPR, 1995 (Kendron) (mg/L)	FIPR, 2005 (Rusch & Seals) (mg/L)	In this study (mg/L)
As	5.0	0.882	ND[a]	<0.002
Ba	100	0.17	ND	0.16-0.07
Cd	1.0	0.01	ND	<0.001
Cr	5.0	0.05	-	0.04-0.02
Pb	5.0	0.1	ND	<0.003
Ag	5.0	0.05	-	<0.005
Hg	0.2	0.005	-	-
Se	1.0	0.1	ND	<0.004

[a]ND = Not detected

Table 5-2. Comparisons of DI water leaching test

Element	% Fraction leached[a]	% Fraction leached[b]
Cr	10	BDL[c]
U	20	--
Zn	58	82

[a]Al Masri et al. (2004)
[b]In this study
[c]BDL = Below detection limit (detection limits are presented in Appendix A)

Table 5-3. Comparison of SPLP with previous leaching studies

Element	% Fraction leached[a]	% Fraction leached[b] (SPLP)
As	3	BDL[c]
Cd	1	BDL
Cr	5	15
Cu	9	21
U	4	--
Zn	3	51

[a]Al-Hwaiti et al. (2010)
[b]In this study
[c]BDL = Below detection limit (Detection limits are presented in Appendix A)

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Table 5-4. Comparison of trace metal concentrations (mg/kg)

Element	Gypsum Wallboard[a]	Phosphogypsum[b]
Al	295	756
As	--	1.9
B	42.5	48.5
Ba	--	38.5
Ca	169360	142590
Cd	3.1	BDL[c]
Co	9.2	BDL
Cr	11.6	1.6
Cu	7.1	1.9
Fe	942	792
K	--	157
Mg	8475	BDL
Mo	2.7	--
Mn	45.6	2.7
Ni	20.1	BDL
S	133821	--
Pb	15.6	3
Se	--	BDL
Zn	16.6	4.3

[a]R. P. Wolkowski (2000)
[b]In this study
[c]BDL = below detection limit

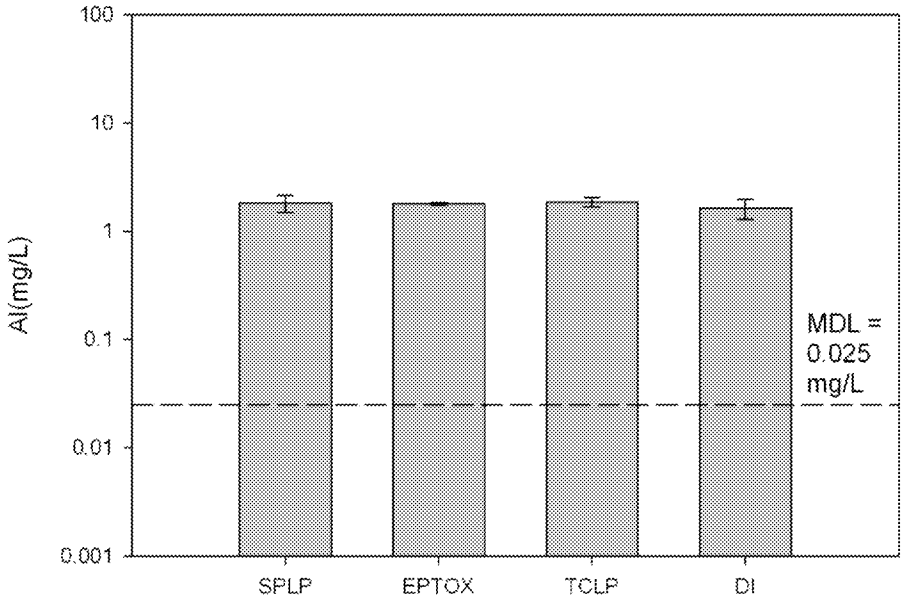

Figure 5-1. Aluminum (Al) concentrations in different batch leaching tests

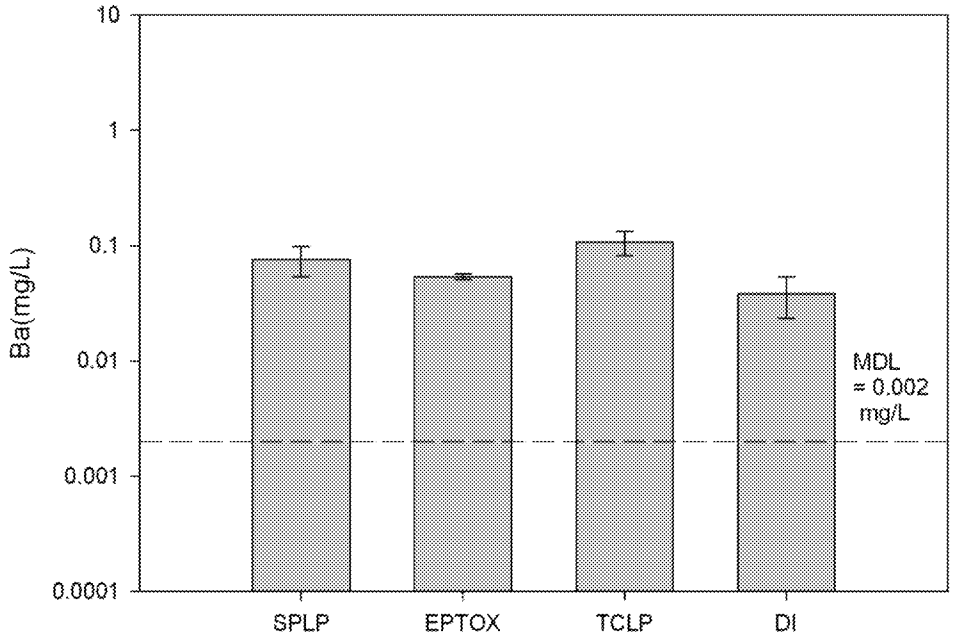

Figure 5-2. Barium (Ba) concentrations in different batch leaching tests

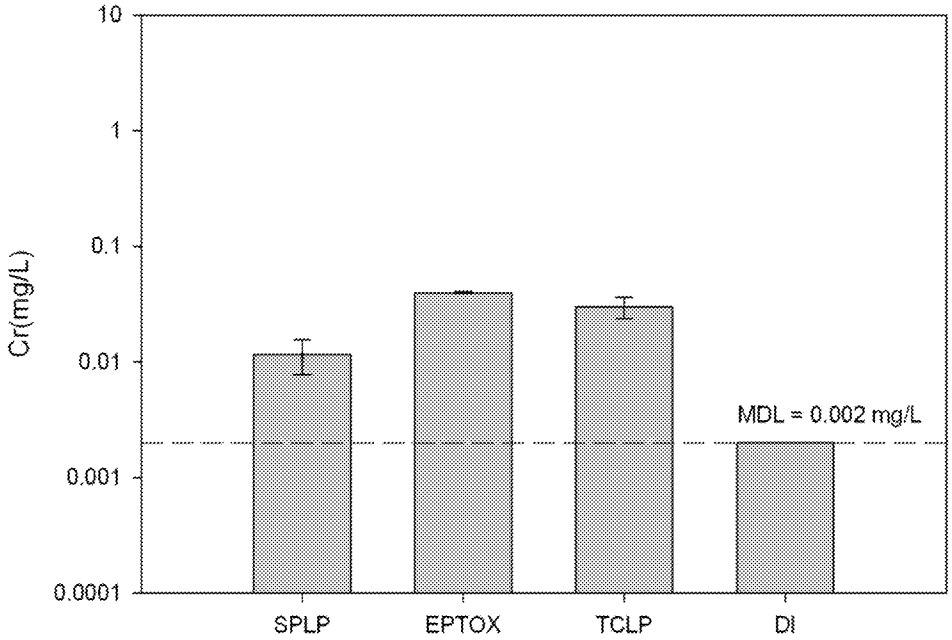

Figure 5-3. Chromium (Cr) concentrations in different batch leaching tests

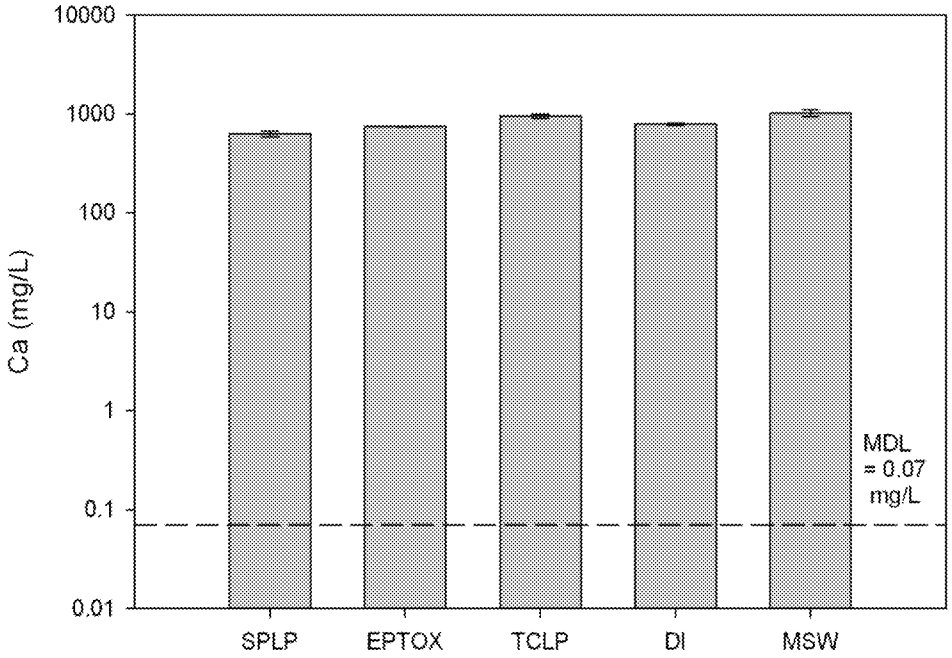

Figure 5-4. Calcium (Ca) concentrations in different batch leaching tests

CHAPTER 6
CONCLUSION

Phosphate mining in Florida is currently one of the state's largest industries, and produces approximately 40 million tons of waste material per year (Burnett et al. 1996). The total and leachable concentrations in PG were characterized for a number of metals. These data were then used to examine a variety of issues associated with determining whether the PG could be beneficially used outside of a landfill (e.g., land application as fill material, soil amendment).

Metal release was assessed using standardized batch leaching tests and additional leaching experiments using specific leaching solutions. To identify potential chemicals of concern, the concentrations of pollutants in the samples were compared with the risk-based standards. Based on the TCLP test, none of the TCLP results exceeded the regulatory toxicity limits showing PG samples did not meet the definition of EPA Toxicity Characteristic under RCRA (40 CFR Part 261.30). Note that Mercury and radionuclide were not tested in this study. However, in the SPLP tests aluminum and iron exceeded their respective Florida groundwater cleanup target levels. When MSW leachate contacts with PG, a few constituents of PG such as calcium and sulfate, may be considerably leached. Increasing sulfate in MSW leachate may be a concern in terms of increased hydrogen sulfide generation; hydrogen sulfide carries concerns of odor and potential deleterious health effects to those exposed. PG samples released considerable amounts of calcium in the TCLP, SPLP, EPTOX and in the leaching test with MSW leachate and DI water.

The TCLP and the SPLP extracted relatively similar metal concentrations (except calcium). Although arsenic was detected at high concentrations in the PG totals

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analysis, it did not leach at concentrations that may pose a risk to human health and the environment in all the leaching tests. In terms of risk assessment, from a direct human exposure pathway, arsenic was found to be the most limiting element. The SPLP results did not find arsenic to pose a risk, but has aluminum and iron concentrations above GWCTL.

It is important to examine potential impacts of PG management to the groundwater because in Florida, over 90% of residents rely on groundwater for a potable water source. Also the results of this study can assist in the consideration of land application of PG.

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APPENDIX A
ICP-AES DETECTION LIMITS

Table A-1. Method Detection Limits

Element	MDL(mg/L)
Ag	0.005
Al	0.025
As	0.002
B	0.009
Ba	0.002
Be	0.001
Ca	0.07
Cd	0.001
Co	0.001
Cr	0.002
Cu	0.002
Fe	0.06
K	0.06
Mg	0.02
Mn	0.002
Mo	0.004
Na	0.44
Ni	0.002
Pb	0.003
Sb	0.006
Se	0.004
Sn	0.006
Sr	0.002
V	0.002
Zn	0.003

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APPENDIX B
TOTAL METAL ANALYSIS DATA

Table B-1. Total metal analysis results of PG samples collected from north wall (mg/Kg)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	955	869	801
As	1.01	2.79	2.06
B	76.66	63.87	40.79
Ba	51.88	51.56	40.59
Be	BDL	BDL	BDL
Ca	179439	191994	142179
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	1.89	2.28	1.56
Cu	2.18	2.67	1.12
Fe	938	944	828
K	114	153	110
Mg	BDL	BDL	BDL
Mn	2.15	2.04	1.95
Na	BDL	BDL	BDL
Ni	BDL	BDL	BDL
Pb	2.66	2.86	3.87
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	5.47	7.06	6.31
V	1.44	1.00	2.24
Zn	4.17	5.19	3.37

[a]BDL = Below detection limit

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Table B-2. Total metal analysis results of PG samples collected from south wall (mg/Kg)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	736	683	795
As	1.19	2.07	2.54
B	46.01	58.57	65.78
Ba	32.31	28.63	31.31
Be	BDL	BDL	BDL
Ca	152259	126366	136369
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	1.74	1.2	1.84
Cu	1.47	1.53	2.78
Fe	807	1067	924
K	204	151	206
Mg	BDL	BDL	BDL
Mn	3.77	4.56	4.20
Na	BDL	BDL	BDL
Ni	BDL	BDL	BDL
Pb	3.94	4.14	2.54
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	3.20	3.21	5.16
V	2.72	1.64	2.62
Zn	5.29	3.78	4.93

[a]BDL = Below detection limit

Table B-3. Total metal analysis results of PG samples collected from east wall (mg/Kg)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	683	619	571
As	3.24	1.21	1.93
B	23.93	20.84	19.94
Ba	41.74	29.91	28.61
Be	BDL	BDL	BDL
Ca	182803	150123	109868
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	2.01	1.11	1.26
Cu	2.56	1.36	1.86
Fe	762	580	502
K	140	145	135
Mg	BDL	BDL	BDL
Mn	3.67	2.3	2.56
Na	BDL	BDL	BDL
Ni	BDL	BDL	BDL
Pb	3.05	2.94	2.26
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	4.64	4.67	2.84
V	1.14	1.14	1.30
Zn	3.65	2.72	2.78

[a]BDL = Below detection limit

Table B-4. Total metal analysis results of PG samples collected from west wall (mg/Kg)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	788	838	728
As	2.80	1.38	1.00
B	70.95	55.5	39
Ba	43.10	48.26	35.16
Be	BDL	BDL	BDL
Ca	107139	118809	113622
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	1.31	0.9	1.86
Cu	2.58	1.71	1.65
Fe	808	620	725
K	170	206	149
Mg	BDL	BDL	BDL
Mn	2.41	1.35	1.46
Na	BDL	BDL	BDL
Ni	BDL	BDL	BDL
Pb	3.14	1.99	2.96
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	4.19	4.08	3.53
V	1.62	1.19	1.04
Zn	4.3	5.45	6.25

[a]BDL = Below detection limit

APPENDIX C
TOXICITY CHARACTERISTIC LEACHING PROCEDURE DATA

Table C-1. TCLP test results of the samples collected from north wall (mg/L)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	1.81	1.66	1.71
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.14	0.11	0.09
Ca	956	887	889
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.03	0.03	0.03
Cu	0.02	0.01	0.02
Fe	0.38	0.58	0.51
K	1.16	1.71	1.64
Mn	BDL	BDL	BDL
Na	1559	1399	1465
Ni	0.07	0.04	0.03
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	3.37	3.08	2.96
V	BDL	BDL	BDL
Zn	0.29	0.18	0.08

[a]BDL = Below detection limit

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Table C-2. TCLP test results of the samples collected from south wall (mg/L)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	1.96	2.18	1.73
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.09	0.1	0.07
Ca	945	1030	892
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.03	0.04	0.03
Cu	0.03	0.02	0.02
Fe	0.34	0.56	0.39
K	4.04	4.37	4.88
Mn	BDL	BDL	BDL
Na	1512	1661	1435
Ni	0.03	0.04	0.02
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	3.02	3.27	2.82
V	BDL	BDL	BDL
Zn	0.15	0.12	0.08

[a]BDL = Below detection limit

Table C-3. TCLP test results of the samples collected from east wall (mg/L)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	1.73	1.69	1.75
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.12	0.12	0.09
Ca	948	971	914
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.03	0.02	0.02
Cu	0.03	0.06	0.02
Fe	0.57	0.52	0.56
K	1.42	1.95	1.83
Mn	BDL	BDL	BDL
Na	1500	1552	1445
Ni	0.02	0.02	0.02
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	3.2	3.25	3.01
V	BDL	BDL	BDL
Zn	0.17	0.15	0.05

[a]BDL = Below detection limit

Table C-4. TCLP test results of the samples collected from west wall (mg/L)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	1.9	2.13	2.08
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.12	0.16	0.09
Ca	953	1003	990
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.03	0.04	0.04
Cu	0.03	0.02	0.02
Fe	0.54	0.36	0.32
K	1.81	1.09	1.92
Mn	BDL	BDL	BDL
Na	1480	1571	1576
Ni	0.03	0.01	0.03
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	3.05	3.17	3.14
V	BDL	BDL	BDL
Zn	0.1	0.26	0.1

[a]BDL = Below detection limit

APPENDIX D
SYNTHETIC PRECIPITATION LEACHING PROCEDURE (SPLP) DATA

Table D-1. SPLP test results of the samples collected from north wall (mg/L)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL*	BDL
Al	2.12	1.79	1.81
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.09	0.07	0.08
Be	BDL	BDL	BDL
Ca	697	632	639
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.01	0.01	0.02
Cu	0.02	0.01	0.02
Fe	0.38	0.46	0.41
K	1.41	1.37	1.34
Na	9.25	7.53	8.66
Ni	0.02	0.03	0.04
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.41	2.4	2.42
V	BDL	BDL	BDL
Zn	0.08	0.1	0.13

[a]BDL = Below Detection Limit

Table D-2. SPLP test results of the samples collected from south wall (mg/L)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL*	BDL
Al	2.12	1.72	1.79
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.06	0.05	0.06
Be	BDL	BDL	BDL
Ca	676	521	602
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.02	0.01	0.01
Cu	0.02	0.03	0.06
Fe	0.3	0.18	0.22
K	3.3	2.26	2.51
Na	10.08	7.84	8.02
Ni	0.01	0.04	0.03
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.25	1.7	1.98
V	BDL	BDL	BDL
Zn	0.08	0.09	0.11

[a]BDL = Below detection limit

Table D-3. SPLP test results of the samples collected from east wall (mg/L)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	1.67	1.55	1.5
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.13	0.1	0.08
Be	BDL	BDL	BDL
Ca	675	637	628
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.01	0.01	0.01
Cu	0.01	0.01	0.01
Fe	0.45	0.31	0.27
K	1.43	1.29	1.38
Na	9.75	8.31	8.98
Ni	0.04	0.02	0.01
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.42	2.28	2.22
V	BDL	BDL	BDL
Zn	0.21	0.14	0.1

[a]BDL = Below detection limit

Table D-4. SPLP test results of the samples collected from west wall (mg/L)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	1.49	1.67	2.64
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.06	0.06	0.07
Be	BDL	BDL	BDL
Ca	593	617	644
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.01	0.01	0.01
Cu	0.02	0.02	0.02
Fe	0.39	0.17	0.22
K	1.19	1.25	1.75
Na	7.22	7.12	10.11
Ni	0.01	0.01	0.02
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.03	2.17	2.18
V	BDL	BDL	BDL
Zn	0.07	0.08	0.14

[a]BDL = Below detection limit

APPENDIX E
EXTRACTION PROCEDURE TOXICITY TEST DATA

Table E-1. EPTOX test results of the samples collected from south wall (mg/L)

Element	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	1.83	1.73	1.80
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.06	0.05	0.05
Be	BDL	BDL	BDL
Ca	752	743	739
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.04	0.04	0.04
Cu	0.19	0.12	0.12
Fe	BDL	BDL	BDL
K	3.46	3.12	2.67
Mg	0.71	0.77	0.78
Mn	BDL	BDL	BDL
Ni	0.06	0.06	0.05
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.34	2.30	2.35
V	BDL	BDL	BDL
Zn	0.26	0.21	0.17

[a]BDL = Below detection limit

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APPENDIX F
MUTIPLE EXTRACTION PROCEDURE TEST DATA

Table F-1. MEP test results of the samples collected from south wall (extraction 1) (mg/L)

Cation	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	1.83	1.73	1.80
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.06	0.05	0.05
Be	BDL	BDL	BDL
Ca	752	743	739
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.04	0.04	0.04
Cu	0.19	0.12	0.12
Fe	BDL	BDL	BDL
K	3.46	3.12	2.67
Mg	0.71	0.77	0.78
Mn	BDL	BDL	BDL
Ni	0.06	0.06	0.05
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.34	2.30	2.35
V	BDL	BDL	BDL
Zn	0.26	0.21	0.17

[a]BDL = Below detection limit

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Table F-2. MEP test results of the samples collected from south wall (extraction 2) (mg/L)

Cation	Sample 1	Sample 2	Sample 3
Ag	BDL	BDL	BDL
Al	2.97	2.81	2.90
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.05	0.05	0.05
Be	0.47	0.46	0.46
Ca	813	801	801
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.06	0.05	0.05
Cu	0.11	0.11	0.10
Fe	BDL	BDL	BDL
K	2.16	2.87	1.12
Mg	0.75	0.53	0.78
Mn	BDL	BDL	BDL
Ni	0.09	0.09	0.09
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.39	2.47	2.41
V	BDL	BDL	BDL
Zn	0.49	0.41	0.35

*BDL = Below Detection Limit

Table F-3. MEP test results of the samples collected from south wall (extraction 3) (mg/L)

Cation	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	2.87	2.75	2.67
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.04	0.04	0.04
Be	0.45	0.45	0.45
Ca	786	782	776
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.05	0.05	0.05
Cu	0.10	0.10	0.09
Fe	BDL	BDL	BDL
K	0.87	0.76	0.66
Mg	0.65	0.50	0.40
Mn	BDL	BDL	BDL
Ni	0.09	0.09	0.09
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.44	2.43	2.37
V	BDL	BDL	BDL
Zn	0.34	0.34	0.31

[a]BDL = Below detection limit

Table F-4. MEP test results of the samples collected from south wall (extraction 4) (mg/L)

Cation	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	2.65	2.65	2.57
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.04	0.04	0.04
Be	0.43	0.43	0.42
Ca	813	801	801
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.05	0.05	0.05
Cu	0.09	0.09	0.08
Fe	BDL	BDL	BDL
K	BDL	BDL	BDL
Mg	0.37	0.38	0.34
Mn	BDL	BDL	BDL
Ni	0.09	0.09	0.09
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.34	2.28	2.28
V	BDL	BDL	BDL
Zn	0.28	0.27	0.27

[a]BDL = Below detection limit

Table F-5. MEP test results of the samples collected from south wall (extraction 5) (mg/L)

Cation	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	2.55	2.53	2.50
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.04	0.04	0.04
Be	0.39	0.39	0.38
Ca	756	747	737
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.05	0.05	0.05
Cu	0.08	0.08	0.08
Fe	BDL	BDL	BDL
K	BDL	BDL	BDL
Mg	0.23	0.21	0.21
Mn	BDL	BDL	BDL
Ni	0.09	0.09	0.09
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.24	2.23	2.18
V	BDL	BDL	BDL
Zn	0.24	0.21	0.20

[a]BDL = Below detection limit

Table F-6. MEP test results of the samples collected from south wall (extraction 6) (mg/L)

Cation	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	2.31	2.30	2.26
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.04	0.04	0.04
Be	0.01	0.03	0.02
Ca	734	723	722
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.05	0.05	0.04
Cu	0.08	0.07	0.07
Fe	BDL	BDL	BDL
K	BDL	BDL	BDL
Mg	BDL	BDL	BDL
Mn	BDL	BDL	BDL
Ni	0.08	0.08	0.08
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	2.14	2.14	2.07
V	BDL	BDL	BDL
Zn	0.19	0.17	0.15

[a]BDL = Below detection limit

Table F-7. MEP test results of the samples collected from south wall (extraction 7) (mg/L)

Cation	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	1.69	1.81	1.73
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	0.03	0.02	0.02
Be	BDL	BDL	BDL
Ca	720	720	714
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.04	0.04	0.04
Cu	0.06	0.06	0.06
Fe	BDL	BDL	BDL
K	BDL	BDL	BDL
Mg	BDL	BDL	BDL
Mn	BDL	BDL	BDL
Ni	0.08	0.08	0.08
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	1.7	1.25	1.55
V	BDL	BDL	BDL
Zn	0.15	0.08	0.09

[a]BDL = Below detection limit

Table F-8. MEP test results of the samples collected from south wall (extraction 8) (mg/L)

Cation	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	BDL	BDL	BDL
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	BDL	BDL	BDL
Be	BDL	BDL	BDL
Ca	710	714	706
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.04	0.04	0.04
Cu	0.06	0.06	0.05
Fe	BDL	BDL	BDL
K	BDL	BDL	BDL
Mg	BDL	BDL	BDL
Mn	BDL	BDL	BDL
Ni	0.08	0.08	0.08
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	BDL	BDL	BDL
V	BDL	BDL	BDL
Zn	BDL	BDL	BDL

[a]BDL = Below detection limit

Table F-9. MEP test results of the samples collected from south wall (extraction 9) (mg/L)

Cation	Sample 1	Sample 2	Sample 3
Ag	BDL[a]	BDL	BDL
Al	BDL	BDL	BDL
As	BDL	BDL	BDL
B	BDL	BDL	BDL
Ba	BDL	BDL	BDL
Be	BDL	BDL	BDL
Ca	705	694	691
Cd	BDL	BDL	BDL
Co	BDL	BDL	BDL
Cr	0.04	0.04	0.04
Cu	0.05	0.04	0.04
Fe	BDL	BDL	BDL
K	BDL	BDL	BDL
Mg	BDL	BDL	BDL
Mn	BDL	BDL	BDL
Ni	0.08	0.08	0.07
Pb	BDL	BDL	BDL
Sb	BDL	BDL	BDL
Se	BDL	BDL	BDL
Sn	BDL	BDL	BDL
Sr	BDL	BDL	BDL
V	BDL	BDL	BDL
Zn	BDL	BDL	BDL

[a]BDL = Below detection limit

APPENDIX G
BATCH LEACHING TEST WITH DI WATER

Table G-1. Metal analysis data after batch test of PG with DI water of NW PG samples (mg/L)

Element	Sample 1	Sample 2
Ag	BDL[a]	BDL
Al	1.50	1.45
As	BDL	BDL
B	BDL	BDL
Ba	0.02	0.02
Ca	816	831
Cd	BDL	BDL
Co	BDL	BDL
Cr	BDL	BDL
Cu	0.11	0.10
Fe	BDL	BDL
K	1.55	1.42
Mn	BDL	BDL
Mo	0.09	0.10
Na	11.51	10.79
Ni	0.02	0.02
Pb	BDL	BDL
Sb	BDL	BDL
Se	BDL	BDL
Sn	BDL	BDL
Sr	2.65	2.54
V	BDL	BDL
Zn	0.10	0.11

[a]BDL = Below detection limit

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Table G-2. Metal analysis data after batch test of PG with DI water of SW PG samples (mg/L)

Element	Sample 1	Sample 2
Ag	BDL[a]	BDL
Al	1.50	1.39
As	BDL	BDL
B	BDL	BDL
Ba	0.03	0.03
Ca	775	804
Cd	BDL	BDL
Co	BDL	BDL
Cr	BDL	BDL
Cu	0.17	0.14
Fe	BDL	BDL
K	3.45	3.50
Mn	BDL	BDL
Mo	0.04	0.03
Na	9.65	9.32
Ni	0.01	0.02
Pb	BDL	BDL
Sb	BDL	BDL
Se	BDL	BDL
Sn	BDL	BDL
Sr	2.23	2.34
V	BDL	BDL
Zn	0.28	0.18

[a]BDL = Below detection limit

Table G-3. Metal analysis data after batch test of PG with DI water of EW PG samples (mg/L)

Element	Sample 1	Sample 2
Ag	BDL[a]	BDL
Al	1.83	1.94
As	BDL	BDL
B	BDL	BDL
Ba	0.05	0.06
Ca	783	779
Cd	BDL	BDL
Co	BDL	BDL
Cr	BDL	BDL
Cu	0.12	0.11
Fe	BDL	BDL
K	1.32	1.72
Mn	BDL	BDL
Mo	0.02	0.03
Na	9.42	9.97
Ni	0.01	0.01
Pb	BDL	BDL
Sb	BDL	BDL
Se	BDL	BDL
Sn	BDL	BDL
Sr	2.59	2.64
V	BDL	BDL
Zn	0.12	0.1

[a]BDL = Below detection limit

Table G-4. Metal analysis data after batch test of PG with DI water of WW PG samples (mg/L)

Element	Sample 1	Sample 2
Ag	BDL[a]	BDL
Al	1.20	2.21
As	BDL	BDL
B	BDL	BDL
Ba	0.04	0.06
Ca	779	772
Cd	BDL	BDL
Co	BDL	BDL
Cr	BDL	BDL
Cu	0.12	0.09
Fe	BDL	BDL
K	2.07	1.47
Mn	BDL	BDL
Mo	0.06	0.02
Na	9.55	11.33
Ni	0.04	0.01
Pb	BDL	BDL
Sb	BDL	BDL
Se	BDL	BDL
Sn	BDL	BDL
Sr	2.39	2.49
V	BDL	BDL
Zn	0.26	0.29

[a]BDL = Below detection limit

APPENDIX H
MSW LEACHATE BATCH LEACHING TEST DATA

Table H-1. Batch leaching test with MSW leachate for PG samples collected from north wall (mg/L)

Element	Blank	Sample 1	Sample 2	Sample 3
Al	0.2	0.2	0.19	0.17
As	0.16	0.14	0.16	0.15
B	6.47	6.59	6.97	6.43
Ba	0.05	0.05	0.04	0.04
Ca	85	1051	1170	1080
Co	0.03	0.03	0.03	0.03
Cr	0.08	0.08	0.08	0.07
Cu	0.02	BDL[a]	BDL	BDL
Fe	5.96	2.60	3.53	2.99
K	847	858	928	853
Mg	36.43	36.09	38.76	35.86
Mn	0.14	0.12	0.13	0.17
Na	1558	1574	1711	1558
Ni	0.11	0.11	0.12	0.13
Sb	0.11	BDL	BDL	BDL
Se	BDL	BDL	BDL	BDL
Sn	BDL	BDL	BDL	BDL
Sr	0.27	3.16	3.48	3.2
V	0.05	0.05	0.05	0.04
Zn	0.05	0.03	0.02	0.03

[a]BDL = Below detection limit

Table H-2. Batch leaching test with MSW leachate for PG samples collected from south wall (mg/L)

Element	Blank	Sample 1	Sample 2	Sample 3
Al	0.2	0.19	0.23	0.24
As	0.16	0.15	0.15	0.16
B	6.47	6.76	6.93	6.99
Ba	0.05	0.03	0.04	0.04
Ca	85	1061	1175	1217
Co	0.03	0.03	0.03	0.03
Cr	0.08	0.08	0.08	0.08
Cu	0.02	BDL[a]	BDL	BDL
Fe	5.96	2.57	3.50	3.66
K	847	903	903	933
Mg	36.43	37.2	37.11	38.13
Mn	0.14	0.12	0.12	0.13
Na	1558	1639	1638	1700
Ni	0.11	0.10	0.10	0.12
Sb	0.11	BDL	BDL	BDL
Se	BDL	BDL	BDL	BDL
Sn	BDL	BDL	BDL	BDL
Sr	0.27	2.95	3.19	3.32
V	0.05	0.06	0.05	0.05
Zn	0.05	0.03	0.03	0.04

[a]BDL = Below detection limit

Table H-3. Batch leaching test with MSW leachate for PG samples collected from east wall (mg/L)

Element	Blank	Sample 1	Sample 2	Sample 3
Al	0.2	0.18	0.13	0.21
As	0.16	0.16	0.14	0.14
B	6.47	7.00	6.34	6.37
Ba	0.05	0.06	0.05	0.03
Ca	85	1119	1154	1157
Co	0.03	0.03	0.03	0.03
Cr	0.08	0.08	0.07	0.07
Cu	0.02	BDL[a]	BDL	BDL
Fe	5.96	2.96	2.74	2.51
K	847	917	869	855
Mg	36.43	37.72	36.06	35.57
Mn	0.14	0.11	0.1	0.1
Na	1558	1670	1577	1550
Ni	0.11	0.11	0.10	0.09
Sb	0.11	BDL	BDL	BDL
Se	BDL	BDL	BDL	BDL
Sn	BDL	BDL	BDL	BDL
Sr	0.27	3.32	3.38	3.38
V	0.05	0.05	0.04	0.04
Zn	0.05	0.03	0.03	BDL

[a]BDL = Below detection limit

Table H-4. Batch leaching test with MSW leachate for PG samples collected from west wall (mg/L)

Element	Blank	Sample 1	Sample 2	Sample 3
Al	0.2	0.19	0.2	0.14
As	0.16	0.14	0.13	0.15
B	6.47	6.79	6.27	6.3
Ba	0.05	0.04	0.06	0.03
Ca	85	1169	1034	903
Co	0.03	0.03	0.02	0.02
Cr	0.08	0.07	0.06	0.07
Cu	0.02	BDL[a]	BDL	BDL
Fe	5.96	2.62	2.41	2.75
K	847	889	819	816
Mg	36.43	36.9	34.34	34.36
Mn	0.14	0.1	0.09	0.1
Na	1558	1620	1485	1480
Ni	0.11	0.1	0.17	0.12
Sb	0.11	BDL	BDL	BDL
Se	BDL	BDL	BDL	BDL
Sn	BDL	BDL	BDL	BDL
Sr	0.27	3.22	2.87	2.56
V	0.05	0.05	0.05	0.05
Zn	0.05	0.04	0.16	0.13

[a]BDL = Below detection limit

APPENDIX I
QUALITY ASSURANCE/QUALITY CONTROL

Table I-1. QA/QC for TCLP

Element	NW1Dup (mg/L	% Recovery	
		MS	MSD
Ag	BDL[a]	91	94
Al	1.81	82	91
As	BDL	110	107
B	BDL	88	87
Ba	0.14	87	103
Ca	960	83	81
Cd	BDL	101	111
Co	BDL	99	109
Cr	0.03	97	107
Cu	0.02	88	91
Fe	0.38	88	98
K	1.17	110	106
Mn	BDL	104	106
Na	1559	85	87
Ni	0.07	83	87
Pb	BDL	101	103
Sb	BDL	86	82
Se	BDL	93	94
Sn	BDL	96	94
Sr	3.37	87	80
V	BDL	92	98
Zn	0.29	88	94

[a]BDL = Below detection limit

Table I-2. QA/QC for SPLP

Element	NW1Dup (mg/L	% Recovery	
		MS	MSD
Ag	BDL[a]	104	105
Al	2.2	110	106
As	BDL	103	107
B	BDL	96	99
Ba	0.09	95	100
Be	BDL	93	97
Ca	700	90	95
Cd	BDL	95	97
Co	BDL	95	99
Cr	0.01	93	98
Cu	0.02	102	108
Fe	0.38	85	84
K	1.41	101	108
Na	9.25	85	94
Ni	0.02	93	98
Pb	BDL	97	101
Sb	BDL	87	96
Sn	BDL	95	102
Sr	2.41	98	100
V	BDL	90	91
Zn	0.08	90	97

[a]BDL = Below detection limit

Table I-3. QA/QC for DI water batch leaching test

Element	NW1Dup (mg/L	% Recovery	
		MS	MSD
Ag	BDL[a]	97	95
Al	1.50	81	85
As	BDL	98	94
B	BDL	84	87
Ba	0.023	93	97
Ca	816	104	100
Cd	BDL	97	99
Co	BDL	87	86
Cr	BDL	98	104
Cu	0.11	85	88
Fe	BDL	93	95
K	1.55	105	102
Mn	BDL	101	99
Mo	BDL	100	103
Na	11.51	83	88
Ni	0.018	85	84
Pb	BDL	118	110
Sb	BDL	95	103
Se	BDL	105	105
Sn	BDL	101	102
Sr	2.65	100	96
V	BDL	85	87
Zn	0.103	94	98

[a]BDL = Below detection limit

Table I-4. QA/QC for MSW batch leaching test

Element	NW1Dup (mg/L	% Recovery	
		MS	MSD
Al	BDL[a]	105	103
As	0.14	101	98
B	6.59	100	95
Ba	0.05	91	93
Ca	1051	95	98
Co	0.03	108	104
Cr	0.08	95	98
Cu	BDL	104	101
Fe	2.60	98	99
K	858	97	99
Mg	36.1	109	103
Mn	0.12	82	86
Na	1574	87	89
Ni	0.11	100	96
Sb	BDL	105	101
Se	BDL	94	97
Sn	BDL	87	93
Sr	3.16	88	94
V	0.05	94	99
Zn	0.03	95	102

[a]BDL = Below detection limit

Table I-5. QA/QC for EPTOX

Element	SW1Dup (mg/L	% Recovery	
		MS	MSD
Ag	BDL[a]	94	99
Al	1.83	87	92
As	BDL	102	97
B	BDL	98	104
Ba	0.06	99	98
Be	BDL	95	98
Ca	752	108	104
Cd	BDL	95	98
Co	BDL	104	101
Cr	0.04	95	98
Cu	0.19	104	101
Fe	BDL	98	99
K	3.46	97	99
Mg	0.71	109	103
Mn	BDL	82	86
Ni	0.06	97	99
Pb	BDL	87	86
Sb	BDL	98	104
Se	BDL	85	88
Sn	BDL	89	94
Sr	2.34	100	102
V	BDL	99	103
Zn	0.26	94	96

[a]BDL = Below detection limit

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ED_005285_00002627-00140

BIOGRAPHICAL SKETCH

Shabnam Mostary was born in Cox's Bazar, a city in Bangladesh. She started her education in Little Jewels School, and continued in Ispahani Public School and College and Chittagong College. She joined to the Civil Engineering Department at Bangladesh University of Engineering and Technology (BUET), where she got her B.Sc. Degree in January 2008. She was accepted into the graduate program in the Department of Environmental Engineering at University of Florida in August 2009. Her research interests include water, wastewater and solid and hazardous waste management. She received her ME from University of Florida in the spring of 2011.

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Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 6/15/2020 1:54:02 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]
Subject: RE: TFI One-pager and supporting materials.
Attachments: TFI_1-pager_6-15-20_tp.docx

Dan and Tom,

Here is a further revised version, Ex. 5 Deliberative Process (DP) Ex. 5 Deliberative Process (DP)
Once you review this, let me know if this looks reasonable to forward to Andrea as a clean copy.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, June 15, 2020 9:25 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Cc: Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Subject: RE: TFI One-pager and supporting materials.

I disagree with the change in the first key point. Lee has suggested the following:

Ex. 5 Deliberative Process (DP)

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Monday, June 15, 2020 8:10 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>

Cc: Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Subject: RE: TFI One-pager and supporting materials.

Good morning,

Ex. 5 Deliberative Process (DP)

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Friday, June 12, 2020 5:27 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Subject: TFI One-pager and supporting materials.

Hi Tom and Dan,

Sorry for the late Friday submission. You have time to look at this on Monday, no need to work over the weekend.

I have a few edits on the one-pager, and I've attached supporting references that I used for you. While there are lots of comments in the margins, I think there are not many changes.

Andrea,

We added a section of talking points, envisioning that the Administrator might be with Mosaic for some time. That took us over the one-page limit. Could you let us know what you think about this draft as well? I'd be interested if we are being presumptive in our approach.

Have a good weekend.

Lee

Lee Ann B. Veal
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Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 6/8/2020 1:07:06 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: TFI - latest agenda
Attachments: TFI_Weekly_updates_agenda_6-3-2020.docx

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 6/5/2020 2:51:56 PM
To: Peake, Tom [Peake.Tom@epa.gov]
Subject: List of week work topics for 6/1/2020 (sorry forgot to send earlier this week)

Hi Tom,

Sorry I realized I hadn't sent you a list of work topics for this week:

Ex. 5 Deliberative Process (DP)

Talk to you in a few,

Joe

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 7/6/2020 6:45:22 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: FW: Revised TFI Briefing for Jon Edwards on July 7
Attachments: TFI Briefing for ORIA Director final 7-6-2020.pptx

This looks like the version that will be sent up.

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, July 06, 2020 2:33 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Starrs, Charles <Starrs.Charles@epa.gov>
Subject: RE: Revised TFI Briefing for Jon Edwards on July 7

Dan,

Thank you. I particularly like the way that you addressed the administrative conditions and options language. Well done.

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, July 06, 2020 1:43 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Starrs, Charles <Starrs.Charles@epa.gov>
Subject: Revised TFI Briefing for Jon Edwards on July 7

Lee:

I have modified the briefing based on our discussion this morning. Please let me know if you see something that doesn't seem to reflect that discussion. Please send it up if you think it is final. Thanks.

Dan

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 9/24/2020 8:03:56 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; White, Rick [White.Rick@epa.gov]
CC: Wieder, Jessica [Wieder.Jessica@epa.gov]
Subject: RE: WIPP and Phosphogypsum transition papers
Attachments: Transition Briefing Paper_TFI Phosphogypsum 9-24-2020.docx

Here is the revised TFI paper, with your comments addressed.

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Tuesday, September 22, 2020 4:11 PM
To: Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: RE: WIPP and Phosphogypsum transition papers

Hi Tom, Dan,

Ex. 5 Deliberative Process (DP)

The PG paper looks good, with just a few edits due to the publicly available info piece and one sentence structure.

Thank you both.

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Tuesday, September 22, 2020 2:52 PM
To: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Wieder, Jessica <Wieder.Jessica@epa.gov>
Subject: WIPP and Phosphogypsum transition papers

All,
The WIPP and PG transition papers are attached for your review and editing pleasure.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 9/24/2020 2:39:05 PM
To: Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]
CC: Peake, Tom [Peake.Tom@epa.gov]
Subject: Agenda for CWMR Weekly 9-24-2020 (eom)
Attachments: Agenda for CWMR Weekly 9-24-2020.docx

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 7/1/2020 8:15:47 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Veal, Lee [Veal.Lee@epa.gov]
CC: Rustick, Joseph [rustick.joseph@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]
Subject: RE: updated briefing materials
Attachments: TFI Briefing for ORIA Director draft 7-1-2020 djs.pptx

Some comments/revisions based on today's discussion.

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Wednesday, July 01, 2020 3:26 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Cc: Rustick, Joseph <rustick.joseph@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>
Subject: updated briefing materials

I resolved most of the comments in the first half of the slides, but did not have time for section on response options.

Jon

Message

From: Stuenkel, David [Stuenkel.David@epa.gov]
Sent: 6/3/2020 2:17:38 PM
To: Veal, Lee [Veal.Lee@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; White, Rick [White.Rick@epa.gov]
CC: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: RE: Collection of TFI "asks"
Attachments: TFI issues and asks from petitions (DOS Comments).docx

Tom, Lee, et al:

I've added responses to (hopefully) address some of the questions raised in the technical section of the document Tom sent yesterday. My comments are red.

David

David Stuenkel, PhD CHP
EPA / OAR / ORIA / RPD / CST
WJC West, Room 1417E
stuenkel.david@epa.gov
(202) 343-9203

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Wednesday, June 3, 2020 09:01
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: Collection of TFI "asks"

Good morning Tom,

Thank you. Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
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From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, June 03, 2020 8:15 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: Collection of TFI "asks"

Lee,

Ex. 5 Deliberative Process (DP)

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From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Tuesday, June 02, 2020 6:04 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: RE: Collection of TFI "asks"

Tom,

Ex. 5 Deliberative Process (DP)

Lee

Lee

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Office: 202-343-9448; Cell: 202-617-4322
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From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Tuesday, June 02, 2020 3:11 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Stuenkel, David <Stuenkel.David@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: Collection of TFI "asks"

Hi,

Ex. 5 Deliberative Process (DP)

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 5/20/2020 6:39:03 PM
To: Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: updated 1-pager and summary tables
Attachments: TFI 1-pager_OAR_5-20-2020 rev2.docx; PG Risk Assessment Summary Table 5-20-2020.docx

Message

From: Egidi, Philip [Egidi.Philip@epa.gov]
Sent: 12/10/2019 2:40:40 PM
To: Ellis, Jerry [Ellis.Jerry@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: QAPP WA6-20 (draft 12-4-19) (003).docx
Attachments: QAPP WA6-20 (draft 12-4-19) (003).docx

Jerry,
Please review this QAPP for the TFI risk assessment review.
If we have any issues, we need to let them know very soon as work needs to happen on this project.
Contact me ore Jon Walsh with any questions you may have.
Thanx
PVE

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 9/21/2020 7:38:54 PM
To: Holden, Patricia [Holden.Patricia@epa.gov]
CC: White, Rick [White.Rick@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Diaz, Charlene [diaz.charlene@epa.gov]
Subject: RE: TFI Materials for Your Review

Thank you Patricia! Have a good evening and I'll 'see' you tomorrow.

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Holden, Patricia <Holden.Patricia@epa.gov>
Sent: Monday, September 21, 2020 3:25 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: White, Rick <White.Rick@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Subject: FW: TFI Materials for Your Review

Lee,

I've formatted the attached memos/letter with the file dated Sept 21 2020 as Tom requested.

Patricia

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, September 21, 2020 2:34 PM
To: Holden, Patricia <Holden.Patricia@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: FW: TFI Materials for Your Review

Hi Patricia,

Jon has cleared on the TFI package. Could you please take your editorial pen to these memorandum/letter documents, adding letterhead where needed and formatting properly? Send them back and then I can get you the whole package including that long list below for submission to CMS. We're not quite ready for CMS yet, however, so no need to look at that today.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Friday, September 18, 2020 3:15 PM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Subject: TFI Materials for Your Review

Jon:

Attached for your review are the components of the package for approval of the TFI request for other use of phosphogypsum. Files include:

1. Transmittal Memo from you to Anne Austin, recommending that she forward the package to the Administrator;
2. Action Memo from Anne to the Administrator, recommending his signature on the approval letter and Federal Register notice;
3. Letter from the Administrator to TFI approving the request;
4. Federal Register package, including;
    - Federal Register notice for Administrator signature;
    - Typesetting request and screenshot of funding information from Compass;
    - Action Information form;
5. 1-page summary (similar to the document provided for the Administrator briefing next week);
6. Communications plan; and
7. Press release.

I believe you already have the communications plan and press release, which have also been shared with OAR communications. Charles Starrs (OGC) has provided some comment on these two documents, which will need to be reviewed with CRIO staff. Charles' comments on the other documents have been addressed.

Please let Lee or me know if you have questions or comments. Thanks.

Dan

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 5/21/2020 7:02:16 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Subject: RE: 3 in 10,000 found

Yes. Now I remember seeing that when we had the question of whether PG had to go in a stack before being used. The answer to that was also yes. Thanks. That clears it up.

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Thursday, May 21, 2020 2:55 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: 3 in 10,000 found

From the SCA report introduction

Ex. 5 Deliberative Process (DP)

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Egidi, Philip [Egidi.Philip@epa.gov]
Sent: 12/9/2019 2:04:17 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; OAR-ORIA-RPD-CWMR [OARORIARPDCWMR@epa.gov]
Subject: RE: Anything for today's management meeting?

NADA
PBE

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, December 09, 2019 6:41 AM
To: OAR-ORIA-RPD-CWMR <OARORIARPDCWMR@epa.gov>
Subject: Anything for today's management meeting?

Tom, Ingrid, Xinyue, Jon M., and Joe are in Carlsbad this week.

This week:

- Ex. 5 Deliberative Process (DP)
- We have draft materials to review for the TFI phosphogypsum application (FR and web, as well as additional TFI documentation);
- Ex. 5 Deliberative Process (DP)

Reminder that the ORIA holiday party is Thursday. Because many people are on travel this week, the RPD potluck is next week.

Anything else?

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 8/5/2020 2:24:42 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]; White, Rick [White.Rick@epa.gov]; Starrs, Charles [Starrs.Charles@epa.gov]
Subject: FW: Status update on TFI Response

FYI

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Idsal, Anne <idsal.anne@epa.gov>
Sent: Tuesday, August 04, 2020 5:59 PM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Cc: Moor, Karl <Moor.Karl@epa.gov>; Cory, Preston <Cory.Preston@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Subject: Re: Status update on TFI Response

Thanks so much for the update.

Anne L. (Idsal) Austin
Principal Deputy Assistant Administrator - Office of Air and Radiation
U.S. EPA

On Aug 4, 2020, at 5:44 PM, Edwards, Jonathan <Edwards.Jonathan@epa.gov> wrote:

<image001.gif>
Anne—I received an email update from Lee Veal on the Fertilizer Institute phosphogypsum alternative use in road construction review activities. Here is a brief summary:

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

If you have any questions, don't hesitate to ask… thanks, Jon

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 9/21/2020 7:04:09 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: TFI Materials for Your Review

That's okay too probably. She has all three, and maybe she hasn't started that one.

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Monday, September 21, 2020 3:02 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: TFI Materials for Your Review

I was just getting ready to hit send asking Patricia to make the change.

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, September 21, 2020 3:01 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>
Subject: FW: TFI Materials for Your Review

Ex. 5 Deliberative Process (DP)

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Sent: Monday, September 21, 2020 2:52 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Subject: RE: TFI Materials for Your Review

Ex. 5 Deliberative Process (DP)

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, September 21, 2020 2:18 PM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Starrs,

Charles <Starrs.Charles@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Subject: RE: TFI Materials for Your Review

Ex. 5 Deliberative Process (DP)

From: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Sent: Monday, September 21, 2020 1:00 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Subject: RE: TFI Materials for Your Review

Everyone--- Thanks for all the hard work on pulling these materials together. They are in very good shape. Please prepare the package/letterhead for formally moving forward, once OGCs (Charles's comments as mentioned below) are resolved.

Ex. 5 Deliberative Process (DP)

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Friday, September 18, 2020 3:15 PM
To: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Subject: TFI Materials for Your Review

Jon:

Attached for your review are the components of the package for approval of the TFI request for other use of phosphogypsum. Files include:

1. Transmittal Memo from you to Anne Austin, recommending that she forward the package to the Administrator;
2. Action Memo from Anne to the Administrator, recommending his signature on the approval letter and Federal Register notice;
3. Letter from the Administrator to TFI approving the request;
4. Federal Register package, including;
    - Federal Register notice for Administrator signature;
    - Typesetting request and screenshot of funding information from Compass;
    - Action Information form;
5. 1-page summary (similar to the document provided for the Administrator briefing next week);
6. Communications plan; and
7. Press release.

I believe you already have the communications plan and press release, which have also been shared with OAR communications. Charles Starrs (OGC) has provided some comment on these two documents, which will need to be reviewed with CRIO staff. Charles' comments on the other documents have been addressed.

Please let Lee or me know if you have questions or comments. Thanks.

Dan

Message

From: Tong, Xinyue [Tong.Xinyue@epa.gov]
Sent: 9/5/2020 12:33:11 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]
CC: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: parameters for FG road base
Attachments: Radon_Concentration_1.jpg; Radon_Concentration_contour.jpg

Ex. 5 Deliberative Process (DP)

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Friday, September 4, 2020 8:04 AM
To: Tong, Xinyue <Tong.Xinyue@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: parameters for FG road base

Xinyue,

Ex. 5 Deliberative Process (DP)

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Tong, Xinyue <Tong.Xinyue@epa.gov>
Sent: Friday, September 04, 2020 7:25 AM
To: Egidi, Philip <Egidi.Philip@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: parameters for FG road base

Good morning Phil,

Thank you for the information on the parameter values.

Ex. 5 Deliberative Process (DP)

Ex. 5 Deliberative Process (DP)

We can talk more about it today or later next week.

Cheers,

From: Egidi, Philip <Egidi.Philip@epa.gov>
Sent: Thursday, September 3, 2020 10:55 AM
To: Tong, Xinyue <Tong.Xinyue@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: parameters for FG road base

Thanks, Dennis. Here are somethings for your consideration

Ex. 5 Deliberative Process (DP)

Thanks
PVE

From: Tong, Xinyue <Tong.Xinyue@epa.gov>
Sent: Wednesday, September 02, 2020 6:50 AM
To: Egidi, Philip <Egidi.Philip@epa.gov>
Subject: parameters for FG road base

Good morning Phil

Ex. 5 Deliberative Process (DP)

Thank you!

Xinyue Tong, Ph.D.
Physical Scientist
OAR/ORIA/RPD/CWMR
U.S. Environmental Protection Agency
Phone: 202-343-9844

Message

From: Egidi, Philip [Egidi.Philip@epa.gov]
Sent: 6/23/2020 3:34:15 PM
To: Peake, Tom [Peake.Tom@epa.gov]
Subject: RE: new file in sharepoint for review--sharepoint issue

Thanx
PVE

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Tuesday, June 23, 2020 9:33 AM
To: Egidi, Philip <Egidi.Philip@epa.gov>
Subject: RE: new file in sharepoint for review--sharepoint issue

Phosphogypsum

Final Technical Review Document folder
PG Risk Assessment Summary Table 5-20-2020_expanded tp
And
TFI – Potential Approval Conditions 06-23-2020

From: Egidi, Philip <Egidi.Philip@epa.gov>
Sent: Tuesday, June 23, 2020 11:23 AM
To: Peake, Tom <Peake.Tom@epa.gov>
Subject: RE: new file in sharepoint for review--sharepoint issue

I don't see the file in SHarepoint so can you tell me which folder to look in?
PVE

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Tuesday, June 23, 2020 8:17 AM
To: Stuenkel, David <Stuenkel.David@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>; Santillan, Eugenio-Felipe <santillan.eugenio-felipe@epa.gov>
Subject: new file in sharepoint for review--sharepoint issue

All,
I had been editing and making comments on the review file on sharepoint. Around 10 am, sharepoint crapped out on me so I had to save the working file under a different name. Please use the file with tp at the end.
Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Appointment

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 3/24/2020 8:44:38 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
CC: Rustick, Joseph [rustick.joseph@epa.gov]

Subject: NESHAP priorities
Attachments: NESHAP_priorities_4-2020.docx
Location: Skype Meeting

Start: 3/27/2020 1:00:00 PM
End: 3/27/2020 2:00:00 PM
Show Time As: Tentative

Discuss program priorities and further development of the attached document

Join Skype Meeting

Trouble Joining? Try Skype Web App

Join by phone

Toll number: Ex. 6 Personal Privacy (PP) (Dial-in Number) English (United States)

Find a local number

Conference ID: Ex. 6 Personal Privacy (PP)

Forgot your dial-in PIN? | Help

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 3/24/2020 8:21:38 PM
To: Peake, Tom [Peake.Tom@epa.gov]
CC: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: At the TFI meeting today...
Attachments: NESHAP_priorities_4-2020.docx

That all sounds great. I'll put something on the calendar for Thursday afternoon.

Please have a look at the attached document, which I've been developing it for the past few weeks with the help of Joe and Stef. On Thursday I would like to talk to you about how we could use it so that you have a sense of the overall priorities, and who is responsible for individual deliverables. I'm reluctant to build a detailed schedule that goes far into the future, but I think we do need to have a clear idea of who is currently working on what, and what comes next for the overall program.

Jon

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Tuesday, March 24, 2020 3:12 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: At the TFI meeting today...

Jon,
We did the TFI meeting. A quick summary is Dave Stuenkel should be in touch with you to discuss the reclaimer issue review that we should get done before TFI comes in with their report. So, please get in touch with Dave to get this issue addressed now that the Energy Fuels immediate issue has gone up the chain.

Stefanie also said you and she talked yesterday about some major upcoming milestones and that you were going to talk with me about the current schedule. Wednesday is crowded but Thursday early or in the afternoon there is time and also on Friday if you want to set something up.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Rustick, Joseph [rustick.joseph@epa.gov]
Sent: 3/23/2020 7:18:00 PM
To: Peake, Tom [Peake.Tom@epa.gov]
Subject: List of work projects for week of 3/23

Hi Tom,

Here are the work projects I'm working on this week:

- Working with Stefanie on a letter to the regions about confirming/updating rad NESHAPS facility info
- Continuing research on road abandonment for TFI
- COR Basic training all day on Tuesday
- Looking over case studies for LAW end of week
- Going through cross-walk talk for the DPA information on WIPP
- Continuing to reach WIPP section info and Appendix SCR/PA

Additional:

- Some of the training I would like to do as time permits is the ICS – Ex. 6 Personal Privacy (PP)
  a Ex. 6 Personal Privacy (PP)

Best,

Joe

Joseph Rustick
Physical Scientist
Radiation Protection Division
Office of Radiation and Indoor Air
Office of Air and Radiation
U.S. Environmental Protection Agency
(202)-343-9682

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 12/6/2019 3:02:36 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: FW: For Review: Draft TFI Webpage
Attachments: TFI draft website_12-5-19.docx

I read over the draft web page, but did not resolve any comments. I'm forwarding it, because after yesterday's conversation, we should probably look at it together with the draft FR notice to decide what direction we plan to take for the purpose of public outreach.

Should you want to make changes in earnest, the working copy is on the G: drive in the directory listed below.

Jon

From: Bacon, Stefanie <Bacon.stefanie@epa.gov>
Sent: Thursday, December 05, 2019 2:33 PM
To: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: For Review: Draft TFI Webpage

Jon:

I provided the draft TFI webpage to Jessica for initial feedback. She had some very good comments. There were only two comments that I couldn't resolve. Could you please see the document in the location below, and address the comments tagged to you?

Ex. 5 Deliberative Process (DP)

Once you've had a chance to review this can go to Dan & Tom.

Thanks!
Stefanie

Stefanie Gera Bacon
U.S. Environmental Protection Agency
Radiation Protection Division
Center for Radiation Information and Outreach
(202) 343-9063 | Bacon.Stefanie@epa.gov

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 12/6/2019 1:48:26 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: TFI FR notice
Attachments: TFI_NOA_FR_notice.doc.docx

Ex. 5 Deliberative Process (DP)

- Jon

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 3/5/2020 6:32:07 PM
To: Stuenkel, David [Stuenkel.David@epa.gov]; Boyd, Mike [Boyd.Mike@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]
CC: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Rustick, Joseph [rustick.joseph@epa.gov]
Subject: reclaimer scenario q's
Attachments: PG Risk Assessment Review - 012720.docx; Reclaimer_Scenario_Rn_questions.docx

David and Mike have agreed to take a look at these, as one gets pretty technical. I welcome all comments.

The SC&A report is not ready for prime time and is provided only for reference purposes.

I'd ideally like to get all comments by COB and send these questions to TFI either this evening or first thing tomorrow.

- Jon

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 4/13/2020 1:26:57 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: Any items to report for the week for our 10 management meeting?
Attachments: Appendix 4b - Response to Second Set of EPA Questions.pdf; Appendix 4a - Response to Jan 16 2020 Questions.pdf

Ex. 5 Deliberative Process (DP)

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Monday, April 13, 2020 7:54 AM
To: OAR-ORIA-RPD-CWMR <OARORIARPDCWMR@epa.gov>
Subject: Any items to report for the week for our 10 management meeting?

Good morning, all!

Ex. 6 Personal Privacy (PP)

Anything to report for the week? A reminder that we have these Monday meetings with Lee because she has a standing Monday afternoon meeting with Jon.

Please let me know if you have anything to add to the several things I plan to report:

Ex. 5 Deliberative Process (DP)

Anything on TFI?

Thanks.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 2/12/2020 1:23:10 PM
To: Walsh, Jonathan [Walsh.Jonathan@epa.gov]; Cherepy, Andrea [Cherepy.Andrea@epa.gov]
CC: Diaz, Charlene [diaz.charlene@epa.gov]; Marbury, Candice [Marbury.Candice@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; White, Rick [White.Rick@epa.gov]
Subject: RE: TFI

Good morning Jon,

Thank you, this is helpful to know.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Tuesday, February 11, 2020 4:30 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Cherepy, Andrea <Cherepy.Andrea@epa.gov>
Cc: Diaz, Charlene <diaz.charlene@epa.gov>; Marbury, Candice <Marbury.Candice@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: TFI

Ex. 5 Deliberative Process (DP)

- Jon

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Tuesday, February 11, 2020 3:46 PM
To: Cherepy, Andrea <Cherepy.Andrea@epa.gov>

Cc: Diaz, Charlene <diaz.charlene@epa.gov>; Marbury, Candice <Marbury.Candice@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: TFI

Andrea,

Here is the revised briefing paper for tomorrow on alternative uses of phosphogypsum. I incorporated your comments and edits.

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Egidi, Philip [Egidi.Philip@epa.gov]
Sent: 12/4/2019 9:13:11 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: WA 6-20 Draft Work Plan and QAPP
Attachments: IGCE Option Phospho Reuse October 2019-v2.xls

Ex. 5 Deliberative Process (DP)

PVE

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, December 04, 2019 2:04 PM
To: Egidi, Philip <Egidi.Philip@epa.gov>
Subject: RE: WA 6-20 Draft Work Plan and QAPP

What was your IGCE?

We need to see what they are planning to do. I have not read the work plan yet, so lets talk tomorrow. I will send an invite. See what you think about the LOE they propose.

Ex. 5 Deliberative Process (DP)

From: Egidi, Philip <Egidi.Philip@epa.gov>
Sent: Wednesday, December 04, 2019 3:45 PM
To: Peake, Tom <Peake.Tom@epa.gov>
Subject: RE: WA 6-20 Draft Work Plan and QAPP

Ex. 5 Deliberative Process (DP)

PVE

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, December 04, 2019 1:35 PM
To: Egidi, Philip <Egidi.Philip@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: RE: WA 6-20 Draft Work Plan and QAPP

Phil,

Ex. 5 Deliberative Process (DP)

I will give you a call later this afternoon or tomorrow.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765

From: Egidi, Philip <Egidi.Philip@epa.gov>
Sent: Wednesday, December 04, 2019 3:06 PM
To: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>
Subject: FW: WA 6-20 Draft Work Plan and QAPP

We need to talk...
Ex. 5 Deliberative Process (DP)
Ex. 5 Deliberative Process (DP)
PVE

Philip Egidi
Environmental Scientist
U.S. Environmental Protection Agency
Radiation Protection Division
Washington, DC
(202) 343-9186 (work)
(970) 209-2885 (Cell)

"The health of the people is the highest law."
Cicero (106 - 43 BC)

From: Stephen Marschke <smarschke@scainc.com>
Sent: Wednesday, December 04, 2019 12:19 PM
To: Phil Egidi <pegidi@tds.net>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>
Cc: Abe Zeitoun <azeitoun@scainc.com>; Stephen Ostrow <sostrow@scainc.com>
Subject: WA 6-20 Draft Work Plan and QAPP

Phil and Jon,

Attached are the draft Work Plan and QAPP for WA 6-20 "Technical Review of the Fertilizer Institute Petition and Risk Assessment for Additional Use of Phosphogypsum in Road Base".

We're looking forward to discussing these draft documents with you during next Monday's 2 pm teleconference. After that we'll make any changes necessary, and send the finalized documents to EPA.

Steve

SC&A

Stephen F. Marschke
Vice President / Nuclear Engineer
(585) 226-6655

This email may contain privileged and confidential information intended only for the use of the specific entity named herein.

Message

From: Walsh, Jonathan [Walsh.Jonathan@epa.gov]
Sent: 6/22/2020 5:21:19 PM
To: Peake, Tom [Peake.Tom@epa.gov]; Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]; Egidi, Philip [Egidi.Philip@epa.gov]
CC: Rustick, Joseph [rustick.joseph@epa.gov]; Stuenkel, David [Stuenkel.David@epa.gov]; Santillan, Eugenio-Felipe [santillan.eugenio-felipe@epa.gov]; Nagata, Jonathan [Nagata.Jonathan@epa.gov]
Subject: FW: Final, Clean Copy of SC&A's Review of TFI's Risk Assessment
Attachments: final report - signature page.pdf; Comments & Responses.docx; PG Risk Assessment Review - 05-21-20.docx; PG Risk Assessment Review - final.docx; PG Risk Assessment Review - final.pdf

All –

I've been through the final report and I'm reasonably satisfied with it.

Ex. 5 Deliberative Process (DP)

Does everyone feel that this is reasonable?

Jon

From: Stephen Marschke <smarschke@scainc.com>
Sent: Wednesday, June 10, 2020 11:40 AM
To: Phil Egidi <pegidi@tds.net>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>
Cc: Abe Zeitoun <azeitoun@scainc.com>
Subject: Final, Clean Copy of SC&A's Review of TFI's Risk Assessment

Good morning Phil and Jon,

Attached are:

1) A final, clean copy of SC&A's review of TFI's risk assessment – Word version
2) A final, clean copy of SC&A's review of TFI's risk assessment – PDF version

3) The signed signature page from the review
4) A EPA Comment & SC&A Response matrix
5) The draft review file with EPA's comments and SC&A's responses

SC&A's technical editor edited the draft file, and I used that file as the point of departure for the final (rather than EPA's markup). We did make sure that all of EPA's comments were addressed in the final, clean copy of the review.

Thanks for the opportunity to work on this interesting project, Steve

Stephen F. Marschke
Vice President / Nuclear Engineer
(585) 226-6655

This email may contain privileged and confidential information intended only for the use of the specific entity named herein.

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 6/22/2020 12:05:55 PM
To: Peake, Tom [Peake.Tom@epa.gov]
Subject: TFI table for Charles
Attachments: TFI Options for Response with Legal Considerations.docx

I was going to send this over, unless you would like to. I thought it best to wait until this morning so it will be near the top of his inbox. It is further embellished after our discussion with Lee last week.

Message

From: Veal, Lee [Veal.Lee@epa.gov]
Sent: 6/17/2020 6:27:57 PM
To: Holden, Patricia [Holden.Patricia@epa.gov]
CC: White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]
Subject: Briefing for Jon

Hi Patricia,

Would you please set up a briefing for Jon Edwards, ideally on July 7 or 8, on "The Fertilizer Institute request for alternative use of phosphogypsum" for 1 hour, using Teams. The attendees should include:
Me, Rick, Tom Peake, Dan Schultheisz, Jon Walsh, Jay Santillan, Jon Nagata, Joe Rustick, David Stuenkel, Phil Egidi, Jon Edwards, Andrea Cherepy, Charles Starrs (OGC).

If Jon is on vacation that week, let's talk about alternatives.

Thank you

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Sent: 6/17/2020 5:51:49 PM
To: Peake, Tom [Peake.Tom@epa.gov]
Subject: Options and Legal Considerations Table for Charles
Attachments: TFI Options for Response with Legal Considerations.docx

I pulled this out and embellished it. Ex. 5 Deliberative Process (DP)
Ex. 5 Deliberative Process (DP) Take a look. We can send it to Charles or have Lee look at it and then send it.

Message

From: Lee, Raymond [Lee.Raymond@epa.gov]
Sent: 9/14/2020 6:50:10 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: TFI files

Yeah, if she is going to be digitally signing off on the action memo, we need to leave it off. Apparently most (if not all) of EPA employees don't have their middle initial on our EPASS profiles. Good to know!

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, September 14, 2020 2:46 PM
To: Lee, Raymond <Lee.Raymond@epa.gov>
Subject: RE: TFI files

One of the items I was going to change on the letter was to add the middle initial. Good to know (but surprising) that the digital signature doesn't include it.

From: Lee, Raymond <Lee.Raymond@epa.gov>
Sent: Monday, September 14, 2020 2:43 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>
Subject: RE: TFI files

Hi Lee,

Co-sign on all of what Dan wrote below in terms of the items I've been involved in.

OP had very minor comments on the draft FR notice that I passed onto Dan & the team last week. Also, we just need to make sure that the signature block for the Administrator should not include his middle initial since we're doing digital signatures. This would apply to Anne as well since she'll be signing the action memo transmitting the notice to the Administrator. Funding on the typesetting is good to go!

Thanks,

Ray

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, September 14, 2020 2:31 PM
To: Veal, Lee <Veal.Lee@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>
Subject: RE: TFI files

We should be aware that some changes may need to be made after the OLEM meeting tomorrow.

OP provided comments on the FR last week, which Ray indicated are minor. I have not incorporated them yet.

I believe Tom may have been revising the Action Memo. Will check with him tomorrow to see if he had changes other than the names.

The Action Information should be good. You made the changes to the stakeholder section and Tom and I agreed.

The letter needs some revision. I have asked Patricia to chase down standard language for the Administrator's correspondence. There are about a half-dozen places where it has some variation of "I approve" that should probably be changed. I also want to do some slight revision in one place for clarity. And there are a couple of formatting things.

The 1-pager, comms plan, press release, and typesetting information are fine from my perspective.

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, September 14, 2020 2:15 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Starrs, Charles <Starrs.Charles@epa.gov>
Subject: TFI files

Hi Dan and Ray,

This is the last copy of the FR notice that I have related to the TFI project, along with all the files that I have that are in final. I'd like to confirm with you a few items and ask for any other changes/corrections:

1. Action Memo from Anne Austin to the Administrator (this was previously from JE to AA). I made the modification under the To and FROM sections. Please confirm this is good to go.
2. TFI Approval 1-pager (was 8 27 2020 now 09 14 2020) I made the change to the bottom line indicating that our recommendation was for the Administrator to sign (not the PDAA).
3. TFI Press Release. This is from Stefanie's email to me on Friday, 9/11.
4. TFI Communications Plan. This is from Stefanie's email to me on Friday, 9/11.
5. TFI FR. Is this the latest? I left this for Anne's signature, and made one change to the footnote that references the approval letter (from Administrator not PDAA). Dan mentioned that Ray Lee may have had a few changes, so let me know if this is the final please.
6. TFI Approval Action Information Form (was 8 27 2020 now 09 14 2020). There were still some redline marks on the Stakeholder Involvement section. I accepted those changes. Let me know if this is final.
7. Response to TFI- Letter PDAA to TFI. I included all the comments that I had from OGC (per Charles' email) but I have not made changes to the signature line or language to reflect that the Administrator will sign. Dan S/CWMR has the pen and will work with Charles. I include it here for reference.
8. Two pdfs, -the typesetting request and the accounting screen. These are from Ray Lee and PMO.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

Message

From: Rosencrantz, Ingrid [Rosencrantz.Ingrid@epa.gov]
Sent: 7/6/2020 1:18:37 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: Anything for today's management meeting?

OK, nice that nothing has been scheduled yet. I'll wait to hear on the ISR stuff as well. Thanks.

Ingrid Rosencrantz
Senior Scientist, Federal Leadership Coach, ACC
Radiation Protection Division
Office of Radiation and Indoor Air
Office of Air and Radiation
U.S. Environmental Protection Agency
202-579-5157

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, July 06, 2020 9:17 AM
To: Rosencrantz, Ingrid <Rosencrantz.Ingrid@epa.gov>
Subject: RE: Anything for today's management meeting?

Is there? I haven't seen anything. I think she wants one, and Jon said we would do one, but nothing scheduled yet. And Sue is checking with OGC management on the "guidance" question.

Don't sweat that OCIR control yet. We don't know what they want from us at this point.

From: Rosencrantz, Ingrid <Rosencrantz.Ingrid@epa.gov>
Sent: Monday, July 06, 2020 9:10 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: Re: Anything for today's management meeting?

There's apparently also a future low activity waste briefing for Anne?

Ingrid Rosencrantz
Senior Physical Scientist and Federal Coach
Radiation Protection Division
Office of Radiation and Indoor Air
Office of Air and Radiation
U.S. Environmental Protection Agency
202-579-5157

On Jul 6, 2020, at 8:21 AM, Schultheisz, Daniel <Schultheisz.Daniel@epa.gov> wrote:

Tom is (hopefully) relaxing this week, although he may attend some meetings. Here are items I have for this week:

- Briefing on TFI phosphogypsum request for Jon tomorrow morning (waiting for Lee's comments on the briefing);

Ex. 5 Deliberative Process (DP)

Anything else?

Also note that Neal will be doing some sort of talk about Chernobyl tomorrow at 11 am. You probably have a meeting invitation, so tune in if you are interested.

Message

From: Egidi, Philip [Egidi.Philip@epa.gov]
Sent: 12/9/2019 4:36:08 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: FW: WA 6-20 Draft Work Plan and QAPP
Attachments: QAPP WA6-20 (draft 12-4-19).docx; WA 6-20 Work Plan - Dec 2019_draft.pdf

---

From: Stephen Marschke <smarschke@scainc.com>
Sent: Wednesday, December 04, 2019 12:19 PM
To: Phil Egidi <pegidi@tds.net>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>
Cc: Abe Zeitoun <azeitoun@scainc.com>; Stephen Ostrow <sostrow@scainc.com>
Subject: WA 6-20 Draft Work Plan and QAPP

Phil and Jon,

Attached are the draft Work Plan and QAPP for WA 6-20 "Technical Review of the Fertilizer Institute Petition and Risk Assessment for Additional Use of Phosphogypsum in Road Base".

We're looking forward to discussing these draft documents with you during next Monday's 2 pm teleconference. After that we'll make any changes necessary, and send the finalized documents to EPA.

Steve

SC&A

Stephen F. Marschke
Vice President / Nuclear Engineer
(585) 226-6655

This email may contain privileged and confidential information intended only for the use of the specific entity named herein.

Message

From: Rosencrantz, Ingrid [Rosencrantz.Ingrid@epa.gov]
Sent: 3/9/2020 12:38:12 PM
To: Schultheisz, Daniel [Schultheisz.Daniel@epa.gov]
Subject: RE: Anything for today's management meeting?

I might mention our plan for outreach to other offices this week on low activity waste. Nothing else from me. Thanks.

Ingrid Rosencrantz
Senior Scientist and Federal Leadership Coach
Radiation Protection Division
Office of Radiation and Indoor Air
Office of Air and Radiation
U.S. Environmental Protection Agency
202-579-5157

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, March 09, 2020 8:27 AM
To: OAR-ORIA-RPD-CWMR <OARORIARPDCWMR@epa.gov>
Subject: Anything for today's management meeting?

Tom, Jay, and Joe are in Phoenix at the Waste Management conference.

Items of interest this week:

Ex. 5 Deliberative Process (DP)

Anything else?

Message

From: Schultheisz, Daniel [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=711CDB8A1BED4570A0ACFDFB38F78D72-DSCHULTH]
Sent: 6/8/2020 2:36:18 PM
To: Hellberg, Dennis [Hellberg.Dennis@epa.gov]
Subject: RE: Additional Info please

Preparing a table to summarize the specific statements TFI is making in its request, either what it is asking for approval on or what constraints it will place on the use of phosphogypsum in road construction. This will be used in conjunction with the technical analysis and OGC input to define our options for responding to the request, including identifying terms and conditions. We anticipate briefing Anne Idsal on the options at the end of the month.

From: Hellberg, Dennis <Hellberg.Dennis@epa.gov>
Sent: Monday, June 08, 2020 10:22 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: Additional Info please

Hi Dan,
For the notes I send out after these meetings, would you provide a little more background on the TFI request table Tom talked about?
Thank you
Dennis

Appointment

From: Schultheisz, Daniel [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=711CDB8A1BED4570A0ACFDFB38F78D72-DSCHULTH]
Sent: 1/23/2020 2:08:29 PM
To: Phil Egidi [pegidi@tds.net]

Subject: FW: PG Discussion TFI, members and EPA
Attachments: Questions_to_TFI_1-16-20.pdf
Location: DCRoomWest1426/OPEI

Start: 1/23/2020 2:30:00 PM
End: 1/23/2020 4:30:00 PM
Show Time As: Tentative

-----Original Appointment-----
From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Friday, January 10, 2020 10:20 AM
To: Veal, Lee; Andy O'Hare; White, Rick; Holden, Patricia; Starrs, Charles; Diaz, Charlene; Schultheisz, Daniel; Peake, Tom; Walsh, Jonathan
Cc: Bacon, Stefanie; Egidi, Philip; Stuenkel, David; Nagata, Jonathan; Santillan, Eugenio-Felipe; Rustick, Joseph
Subject: PG Discussion TFI, members and EPA
When: Thursday, January 23, 2020 9:30 AM-11:30 AM (UTC-05:00) Eastern Time (US & Canada).
Where: DCRoomWest1426/OPEI

Hi,
Just a resend of our invitation to confirm our time slot of 9:30-11:30 am (I'd reserved the room for a longer period by mistake.)

Lee

Conference Number 1 Ex. 6 Personal Privacy (PP) Conference ID Ex. 6 Personal Privacy (PP)

Next meeting with TFI et. al. Please add attendees as appropriate.

From: Andy O'Hare
Sent: Tuesday, January 7, 2020 4:09 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Subject: Thursday, January 23

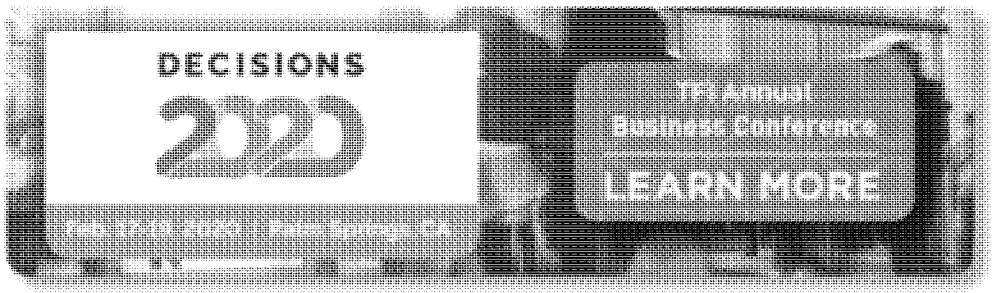
Lee,

Looks like Thursday morning, January 23rd is the preferred date from my end. How about 9:30-11:30 a.m.?

Regards,
Andy

Andrew (Andy) T. O'Hare, CAE
Vice President, Public Policy
The Fertilizer Institute
425 Third Street, SW
Suite 950
Washington, DC 20024
(202) 515-2704 (office)
(202) 270-0094 (cell)
aohare@tfi.org

THE FERTILIZER INSTITUTE



Appointment

From: Schultheisz, Daniel [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=711CDB8A1BED4570A0ACFDFB38F78D72-DSCHULTH]
Sent: 8/14/2019 2:24:46 PM
To: Rustick, Joseph [rustick.joseph@epa.gov]

Subject: FW: TFI Follow-up Briefing
Attachments: Phosphogypsum_TFI_8-14-2019_final.pptx
Location: DCRoomWest1317

Start: 8/14/2019 8:00:00 PM
End: 8/14/2019 9:00:00 PM
Show Time As: Tentative

-----Original Appointment-----
From: Edwards, Jonathan <Edwards.Jonathan@epa.gov>
Sent: Wednesday, August 14, 2019 10:24 AM
To: Edwards, Jonathan; Cherepy, Andrea; Veal, Lee; White, Rick; Peake, Tom; Schultheisz, Daniel; Egidi, Philip; Walsh, Jonathan
Cc: Diaz, Charlene; Holden, Patricia
Subject: TFI Follow-up Briefing
When: Wednesday, August 14, 2019 4:00 PM-5:00 PM (UTC-05:00) Eastern Time (US & Canada).
Where: DCRoomWest1317

Call-in information: Ex. 6 Personal Privacy (PP) ID: Ex. 6 Personal Privacy (PP)

POC: Candice Marbury Ex. 6 Personal Privacy (PP)

Message

From: Schultheisz, Daniel [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=711CDB8A1BED4570A0ACFDFB38F78D72-DSCHULTH]
Sent: 12/2/2019 2:15:53 PM
To: Egidi, Philip [Egidi.Philip@epa.gov]
Subject: RE: Anything for today's management meeting?

How are things going? Seems like the weather has been acting up since you started the drive out.

From: Egidi, Philip <Egidi.Philip@epa.gov>
Sent: Monday, December 02, 2019 9:01 AM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: Anything for today's management meeting?

NADA
PVE

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, December 02, 2019 6:51 AM
To: OAR-ORIA-RPD-CWMR <OARORIARPDCWMR@epa.gov>
Subject: Anything for today's management meeting?

Tom is on leave today. I will be at DOE in Germantown most of tomorrow, and teleworking otherwise.

Things going on this week:

- Final preparations for WIPP trip next week;
- Working on a 1-pager for the MOU with NRC;
- Working on a Federal Register notice for the TFI phosphogypsum application;
- WIPP inspection reports hopefully clear CWMR review this week;
- SNL baseline FR notice published last Wednesday (45-day comment period).

Anything else?

Message

From: Schultheisz, Daniel [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=711CDB8A1BED4570A0ACFDFB38F78D72-DSCHULTH]
Sent: 8/14/2019 1:59:46 PM
To: Holden, Patricia [Holden.Patricia@epa.gov]
Subject: FW: TFI/phosphogypsum briefing for Jon Edwards
Attachments: Phosphogypsum_TFI_8-14-2019_final.pptx

From: Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Sent: Tuesday, August 13, 2019 3:19 PM
To: Diaz, Charlene <diaz.charlene@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Bacon, Stefanie <Bacon.stefanie@epa.gov>; Egidi, Philip <Egidi.Philip@epa.gov>
Subject: TFI/phosphogypsum briefing for Jon Edwards

It looks like tomorrow's briefing may have been cancelled, but here are the slides in case the show can go on.

Message

From: Schultheisz, Daniel [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=711CDB8A1BED4570A0ACFDFB38F78D72-DSCHULTH]
Sent: 10/15/2020 1:45:28 PM
To: Nesky, Anthony [Nesky.Tony@epa.gov]
CC: Lee, Raymond [Lee.Raymond@epa.gov]
Subject: FW: technical review document and road abandonment document
Attachments: Memo for Road Abandonment Final 101520 signed.pdf

This document should be posted on the web site (and the docket).

From: Rustick, Joseph <rustick.joseph@epa.gov>
Sent: Thursday, October 15, 2020 9:43 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Holden, Patricia <Holden.Patricia@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: technical review document and road abandonment document

Hi Lee,

Attached is my signed version of the road abandonment memo.

Best,

Joe

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Thursday, October 15, 2020 9:14 AM
To: Holden, Patricia <Holden.Patricia@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: RE: technical review document and road abandonment document

Hi,
Thank you Patricia.

Joe,
Please type in the signature date at the top of the memo, even though it does note it in an electronic signature in Adobe.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Holden, Patricia <Holden.Patricia@epa.gov>
Sent: Thursday, October 15, 2020 7:37 AM

To: Rustick, Joseph <rustick.joseph@epa.gov>; Veal, Lee <Veal.Lee@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>; White, Rick <White.Rick@epa.gov>
Subject: FW: technical review document and road abandonment document

Good Morning,

The attached documents titled "Memo for Road Abandonment Final 101520 was updated.

Patricia

From: Veal, Lee <Veal.Lee@epa.gov>d
Sent: Wednesday, October 14, 2020 7:02 PM
To: Holden, Patricia <Holden.Patricia@epa.gov>; Diaz, Charlene <diaz.charlene@epa.gov>
Cc: Peake, Tom <Peake.Tom@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>; Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: FW: technical review document and road abandonment document

Hi Patricia and Charlene,

Could you please help us get this onto letterhead and it proper format for me? I think that this might be Joe's first official technical analysis memo that I've seen (as an EPA employee).

Could you double check all page numbering (for the 3 attachments), margins, headers, etc to ensure it meets EPA correspondence manual requirements? We are going to make this available in the public docket, so it will have to represent!

Thank you in advance.

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Wednesday, October 14, 2020 5:10 PM
To: Veal, Lee <Veal.Lee@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>; Rustick, Joseph <rustick.joseph@epa.gov>
Subject: technical review document and road abandonment document

Lee,
Attached are the latest versions of the technical review and road abandonment documents (guys, please confirm).

The technical review document (Sept. 30 version) has one last comment from me that you need to decide on and there is the draft watermark that needs to be deleted once you are done.

Dan and I looked at the road abandonment memo and Joe has addressed our comments.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

Message

From: Schultheisz, Daniel [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=711CDB8A1BED4570A0ACFDFB38F78D72-DSCHULTH]
Sent: 8/24/2020 4:52:47 PM
To: Veal, Lee [Veal.Lee@epa.gov]
Subject: RE: Revised Draft FR Notice for TFI

Sure. I am available.

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, August 24, 2020 12:35 PM
To: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

Do you want to join me in chatting with him later today?

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, August 24, 2020 9:53 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

And no, this has not been discussed with Charles, as far as I know. It just occurred to me (perhaps it had already occurred to others).

From: Schultheisz, Daniel
Sent: Monday, August 24, 2020 9:41 AM
To: Veal, Lee <Veal.Lee@epa.gov>; Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

Ex. 5 Deliberative Process (DP)

From: Veal, Lee <Veal.Lee@epa.gov>
Sent: Monday, August 24, 2020 9:36 AM
To: Peake, Tom <Peake.Tom@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

Hi Tom and Dan,

I added in Ray Lee and Jon Walsh for completeness.

Ex. 5 Deliberative Process (DP)

Lee

Lee Ann B. Veal
Director, Radiation Protection Division
Office of Radiation and Indoor Air
Office: 202-343-9448; Cell: 202-617-4322
www.epa.gov/radiation

From: Peake, Tom <Peake.Tom@epa.gov>
Sent: Monday, August 24, 2020 9:26 AM
To: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>
Cc: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Subject: RE: Revised Draft FR Notice for TFI

I just looked at it and deleted a couple of comments since Dan addressed them.

I think Dan did a terrific job adding in relevant background and focusing the discussion.

I think we can review this in parallel.

Tom Peake
US EPA Radiation Protection Division
Director, Center for Waste Management and Regulations
phone: 202-343-9765
cell phone: 202-465-5904

From: Schultheisz, Daniel <Schultheisz.Daniel@epa.gov>
Sent: Monday, August 24, 2020 9:16 AM
To: Peake, Tom <Peake.Tom@epa.gov>; Walsh, Jonathan <Walsh.Jonathan@epa.gov>
Cc: Veal, Lee <Veal.Lee@epa.gov>; White, Rick <White.Rick@epa.gov>; Lee, Raymond <Lee.Raymond@epa.gov>
Subject: Revised Draft FR Notice for TFI

You can edit this and also access it through Teams without being in the VPN. Should it also go to the rest of the team at this point? You will see a question for Joe and Stefanie, which I will also send them separately.

Appointment

From: Holden, Patricia [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=9B6B83191FEF4C1C982BAE41943BC99F-HOLDEN, PAT]
Sent: 12/3/2020 1:24:10 PM
To: Veal, Lee [Veal.Lee@epa.gov]; White, Rick [White.Rick@epa.gov]; Peake, Tom [Peake.Tom@epa.gov]; Dan Schultheisz (Schultheisz.Daniel@epa.gov) [Schultheisz.Daniel@epa.gov]; Walsh, Jonathan [Walsh.Jonathan@epa.gov]
CC: Diaz, Charlene [diaz.charlene@epa.gov]

Subject: Informal Discussion of TFI Clarification Memo
Attachments: TFI_PG_Determination_Clarification_Request_12-1-20 final (002).pdf
Location: Microsoft Teams Meeting

Start: 12/7/2020 4:00:00 PM
End: 12/7/2020 4:30:00 PM
Show Time As: Busy

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