Risk and Character of Radioactive Waste at the West Lake Landfill, Bridgeton, Missouri

Robert E. Criss
Department of Earth and Planetary Sciences
Washington University, St. Louis, MO

Summary

In 1973, 8700 tons of radionuclide-bearing "leached barium sulfate" was allegedly dumped in an unlined landfill in Bridgeton, MO that was not licensed to receive radwaste. This report finds that 1) the chemical and physical character of the radioactive material has not been adequately characterized, and barium sulfate is probably not a major constituent; 2) the alpha and beta emissions of this material will increase 10x to 100x over present levels, reaching maximum activity in about 9000 years; 3) the landfill has no protective barriers and a proximal subsurface fire; 4) the site has several hydrologic and geologic risk factors that magnify its unsatisfactory location in a populated area; 5) nuclear material has been in contact with percolating waters and with a fluctuating water table; 6) groundwaters contaminated with radionuclides have migrated far from the original location of disposal; 7) background levels of radiation have been overstated, while other risks have been underestimated; and 8) neither the potentially responsible parties nor EPA have acquired essential data, have properly interpreted their data, or considered relevant reports published by disinterested parties. These items are addressed in order below, followed by some recommendations.

1. Chemical and physical character of the radioactive material

According to NRC (1982, p. 4), in 1973 approximately 8700 tons of "leached barium sulfate" containing approximately 7 tons of U_3O_8 were "erroneously dumped" by Cotter Corporation in the West Lake Landfill. Allegedly, this material originated at Mallinckrodt Chemical Works in downtown St. Louis, where uranium was extracted from ore for the Manhattan Project (e.g., NAP, 1995, p. 7). Surplus radioactive materials and processing wastes were subsequently moved several times, first to the "Airport Site" along Coldwater Creek, north of Lambert Field, then to the Latty Avenue Site, east of the airport and also on Coldwater Creek, and finally, some of this hazardous material was delivered to West Lake Landfill, following admixture of an estimated 39,000 tons of "soil" for dilution (NRC, 1988, p. 1).

No available reports mention any accurate analysis of the chemical, physical or radiological character of the radioactive materials dumped at West Lake. Note that neither barium nor sulfate are contaminants of concern, nor is the uranium concentration of the radwaste, alleged to be similar to that of low-grade uranium ore, of primary environmental importance. Instead, the real concerns involve the concentrations of the short-lived, daughter radionuclides in the ^{238}U, ^{235}U and ^{232}Th decay chains, particularly ^{230}Th, ^{226}Ra, ^{228}Ra, ^{223}Ra, ^{210}Po, and three daughter radon isotopes, in the radwaste that was dumped. It is likely that complete analyses of the original radwaste, and possibly even actual samples of the "leached barium sulfate", exist today. Also of primary concern is the physical nature of the radwaste, particularly the texture, surface character and grain size of the "barium sulfate", as these properties have essential bearing on how readily radionuclides can be released from this material into percolating waters and ground waters.

NRC (1982, p. 20) concludes "Chemical analyses reveal high concentrations of barium and sulfates in the radioactive deposits. These results tend to confirm the reports that this contaminated material is uranium and uranium ore, contained in leached barium sulfate residues, and presumably transferred

WLLFOIA4312 - 001 - 0014462

from the Latty Avenue Site in Hazelwood, Missouri." This statement is simplistic and untrue, and in a later report, NRC (1988, p. 11) points out that material with extremely high ^{230}Th to ^{226}Ra ratios, up to 300:1, "might have been transferred along with the barium sulfate residues." First, the barium (< 2500 ppm) and sulfate (< 125 ppm) concentrations in five samples of the contaminated material (see NRC, 1982, Table 13, p. 109) are far too low, by ~100x and ~1000x respectively, than concentrations expected for material containing appreciable amounts of barium sulfate. Second, the barium to sulfate ratios of these samples range from about 17 : 1 to 105 : 1, when stoichiometric barium sulfate has a $Ba:SO_4$ weight ratio of only 1.43 : 1. It is thus very likely that a large amount, if not most, of the radionuclides at West Lake are not contained in barium sulfate, but instead are incorporated in other types of processing waste that could be far more reactive, soluble and leachable than barium sulfate.

Instead of addressing this primary issue, numerous reports have focused on analyzing and interpreting samples of landfill dirt, ambient air, ground and surface waters, etc. While these costly and continuing efforts have provided some useful information about environmental site hazards, they cannot answer the key question, which is, what type of radwaste was originally dumped at West Lake Landfill?

2. Radiological character of waste

Available data and surveys provide the following information about the West Lake radwaste:

NRC (1988, p. 12, 13) estimates that landfill wastes contain an average concentration of about 90 pCi/g, and that the site contains a total activity of approximately 3 Ci due to ^{238}U, 3 Ci due to ^{234}U, 1400 Ci due to ^{230}Th, and 14 Ci due to ^{226}Ra decay. Both ^{222}Rn and ^{219}Rn were detected, as well as ^{226}Ra and ^{223}Ra, so products of both the ^{238}U and ^{235}U decay chains are present at the site (NRC, 1982, p. 13; also Table 5). Elevated ^{228}Ra is also present, which is part of the ^{232}Th decay chain (EMSI, 2012, Figs. 6, 7). Involvement of these three decay chains means that a minimum of 46 different radionuclides representing 12 different elements are present at West Lake Landfill (e.g., Faure, 1986).

Onsite ^{226}Ra concentrations in soils as high as 21,000 pCi/g were measured, compared to estimated background levels of 2 pCi/g (NRC 1982, p. 13). Elevated radium contents above the EPA's MCL of 5 pCi/l are also widespread in both the alluvial and bedrock aquifer within about 1500 feet of Areas 1 and Area 2 (e.g., EMSI, 2012, Figs. 8, 9). Airborne surveys established that external radiation levels exceeding 100μR/hr (NRC, 1982, p. 5), while distal samples were <10 μR/hr (Fig. 2, p. 26). Levels recorded one meter above Area 2 were as high as 3-4 mR/hr, or as much as 400x higher than background (NRC 1982, p. 11). NRC (1982, p11) reports that the subsequent addition of soil cover and construction debris to Areas 1 and 2 diminished these levels several fold.

All surface soil samples "contain high levels of ^{230}Th. The ratio of ^{230}Th to ^{226}Ra is about 20…" (NRC, 1982, p. 14). Elsewhere the ^{230}Th to ^{226}Ra ratio is reported to be "5 to 50" (NRC, 1982, p. 20), or "4:1 to 40:1" but also that samples "along the berm range up to 70:1" (NRC, 1988, p. 11). NRC (1988, p. 14) also points out that "… the large but variable ratio of Th-230 to Ra-226 and its decay products makes the delineation of cleanup more difficult. When the ratio is so large (20:1 or more), even a small concentration of Ra-226 in 1988 implies such a large concentration later that it will be necessary to employ more difficult measurements to confirm that the cleanup has been satisfactory."

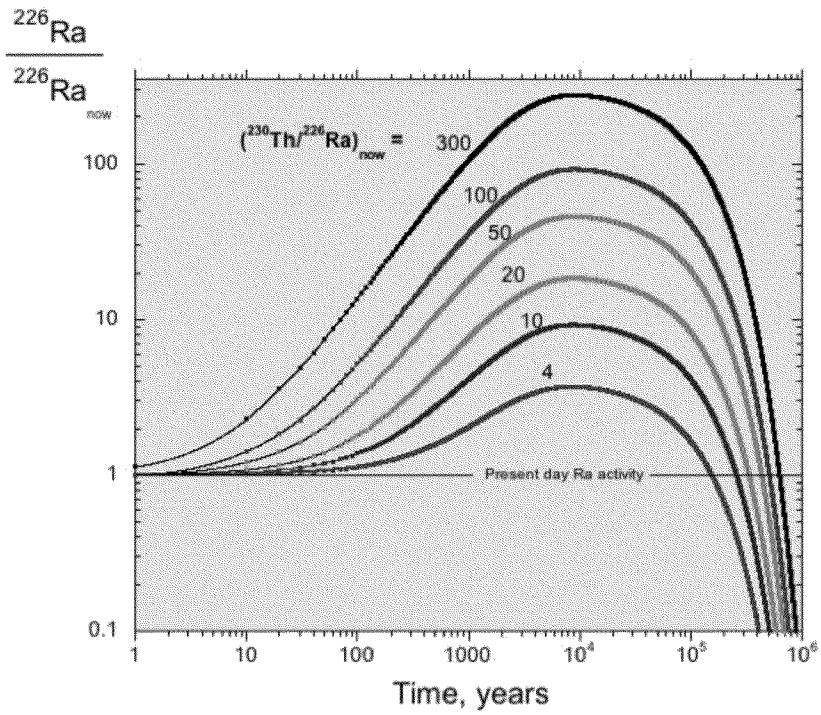
Importantly, because the concentrations of short-lived radionuclides will progressively increase, the radioactivity at the site will likewise increase for the foreseeable future. For example, according to NRC (1988, p. 13), if the present day activity of ^{230}Th is estimated to be 100 times that of ^{226}Ra, then

WLLFOIA4312 - 001 - 0014463

the alpha activity due to ^{226}Ra decay will increase fivefold over present levels in 100 years, nine-fold in 200 years, and 35-fold in 1000 years. The following equation and figure were developed to clarify this problem:

$$!!!!\frac{!!"!"}{!!"!!!"} \; ! \; \left(\frac{!"\#!!}{!!"!"}\right)_{!"} \left(\frac{\lambda_{!!"}}{\lambda_{!!"!!!"\#}}\right)\left(e^{!!!"\#t} - !^{-!!!"!}\right) \; ! \; e^{!\lambda_{!!"!}}!!! \;\; !!!\,!!!\,!"!1$$

Equation 1. Relationship between the future activity of ^{226}Ra and elapsed time t for any assumed, present-day (pd) activity ratio of ^{230}Th to ^{226}Ra (first term on right, above). The ^{226}Ra activities are normalized to present day levels in the ratio on the left hand side. Here, λ_{226} and λ_{230} are the well-known decay constants of ^{226}Ra and ^{230}Th, which are 4.3E-4/y and 9.0E-6/y, respectively. Additional production of ^{230}Th by decay of long-lived uranium isotopes is neglected, but such production could only slightly increase the maximum ^{226}Ra values that will be attained ~ 9000 years from now, while lengthening the time required for the ^{226}Ra activity to eventually decrease back to present day values.



!

Figure 1. Growth of ^{226} Ra activity over present levels, calculated using Eq. 1 as a function of time from now and the present-day ^{230}Th to ^{226}Ra activity ratio (labeled curves). The latter is assumed to vary from 4x to 300x, representing the range of measured and estimated values reported by NRC (1982, 1988). Available data and these calculations indicate that alpha radiation emitted by radium-226 in landfill radwaste will increase by a factor of 10x to 100x, attaining a maximum activity about 9000 years from now. Radon-222 concentrations will increase by the same 10x to 100x factor, as will the concentrations and radioactive emanations of many other short-lived radionuclides. After the maximum levels of radioactivity are attained, the activity will slowly return back to present-day values, but this will require several hundred thousand years.

WLLFOIA4312 - 001 - 0014464

The radioactivity of a nuclide that undergoes decay while simultaneously being produced by decay of a parent radionuclide is easily calculated (e.g., Faure, 1986). I used those well-known results to derive Equation 1, which facilitates direct calculation of future ^{226}Ra activities, relative to its present-day activity, as a function of time (years) and any assumed, present-day ^{230}Th to ^{226}Ra activity ratio. Figure 1 shows that the ^{226}Ra activity at West Lake Landfill will steadily increase for ~9000 years, when the levels will probably be 10 to 100-times greater than the present-day ^{226}Ra activity. Of course, each of many subsequent, short-lived radionuclides in the ^{238}U decay chain will also increase by that same factor of 10 to 100x, including ^{222}Rn, ^{218}Po, ^{214}Bi, ^{210}Pb, and others. In fact, every time in the future that an ^{226}Ra atom disintegrates by releasing an alpha particle, new daughter radionuclides will be generated that will themselves quickly decay, together releasing 4 additional alpha particles, plus 4 beta particles and numerous gamma rays (e.g., see Walker et al., 1989; Faure, 1986).

3. Nature of the landfill

According to NRC (1982, pp. iii, 3), about 15 acres of the West Lake landfill to depths up to 20 feet are contaminated with radwaste, all situated on the alluvial floodplain of the Missouri River. Other chemical wastes, unrelated to the radioactive contamination, are also present including heavy metals, oils and halogenated hydrocarbons (NRC, 1982 p. 5). More recently, EPA (2008, p. 2) concluded that about 10 acres of Radiological Area 1 are impacted by radionuclides at depths ranging up to 15 feet, while about 30 acres of Area 2 are impacted by radionuclides at depths generally ranging to 12 feet. Yet another 4.5 acre area, an adjacent property variously referred to as the "Buffer Zone/Crossroad Property", or the "Ford Property", or the "Farmer's field", has been "superficially contaminated" (EPA, 2008, p. 2, 10), and subsequently has been "scraped and regraded ". In spite of this intervention, almost half of the surface soil samples recently collected from this latter area had radionuclide concentrations significantly above background levels (EPA, 2008, p. 17).

West Lake Landfill has no engineering barriers. Specifically, it has no basal clay liner, no plastic sheeting, no internal cells, no leachate collection system, nor any type of protective cap, all of which are standard requirements for modern landfills. Instead, West Lake Landfill is a chaotic pile of debris covered by unmanaged "natural" vegetation, surrounded by a fence with radioactive hazard signs. This landfill is an unsuitable host for any type of radwaste, industrial waste, chemical waste, or even ordinary domestic waste. For example, Figure 3-29 of McLaren Hart (1996) confirms that Area 2 of West Lake Landfill is a 30 to 45 foot-deep pile of material dumped directly on unconsolidated alluvial sand deposits, that in turn overlie Mississippian limestone units.

In addition to the above problems, an underground fire is currently ongoing in the municipal landfill (OU-2) that is immediately south of Area 1 of OU-1. Such fires can burn for years, creating high underground temperatures, and releasing carbon monoxide, dioxins, VOCs and other noxious chemicals, and particulates into air (e.g., EPA 1995, p. 1.3 to 1.6; FEMA, 2002, p. 15). Numerous people who reside near the landfill complained about odor and health problems at the January 17, 2013 public meeting in Bridgeton. Risks for adjacent, radionuclide-bearing OU-1 include but are not restricted to the following 1) fire can spread from OU-2 into OU-1, particularly because demolition and construction landfills are known to have much higher fire risk than municipal landfills (FEMA, 2002, p. 7); 2) subterranean fires can result in landfill collapse, landslides and slumping, endangering personnel and exposing dangerous materials to the surface (FEMA, 2002, p. 5, 25); 3) landfill fires have high explosion risk because of methane, gas cylinders, and drums; 4) high temperatures and smoke could mobilize

WLLFOIA4312 - 001 - 0014465

radionuclides into surface water, groundwater and air. For example, toxic chemicals and radionuclides including alpha-emitting radon isotopes can become attached to carbon-rich particulates, then disseminated in smoke (e.g., Foss-Smith, 2010); 5) explosions, collapse, and other problems can unearth radionuclides, which can then spread over large areas as airborne dust or in water. This situation exemplifies how both unanticipated risks and unrealistic risk assessments pertain to sites that require isolation of dangerous materials for thousands of years.

4. Hydrologic and Geologic Risk Factors of the West Lake Landfill Site

NRC (1982, p. 3) points out that the West Lake Landfill is located on the Missouri River floodplain, within a combined commercial, rural and industrial area about 1.5 miles from the Missouri River. Several hazards are associated with this site, including flood risk, liquefaction risk, landslide risk, groundwater contamination, a subterranean fire in a proximal landfill, risk of impeding freeway and road traffic, risk of disrupting essential municipal infrastructure or activities, and risk of harm to proximal humans and animals. Attention below is confined to the hydrologic and geologic risks.

EPA (2008, p. 6) argues that flood risk to the landfill is minimal because the area is protected by the "500-year" Earth City levee. Such simplistic statements ignore persuasive evidence that flood levels on the lower Missouri and Mississippi Rivers have been increasing with time (Criss and Shock, 2001), as clearly shown by the actual flood record in Missouri over the last 30 years. Even since 2008, numerous all-time record flood levels have been set along huge reaches of the Missouri and Mississippi Rivers, specifically in northeast Missouri and Iowa in 2008, and in both northwest and southeast Missouri in 2011. Specifically, many sites experienced "100 to 500-year floods" during the last 5 years. As examples, many gaging stations along the Missouri River in northwest Missouri including St. Joseph and Rulo recorded floodwaters within 3 inches of the "500-year" level in 2011. Similarly, floodwaters at Hannibal Missouri rose above the "500-year" level in 1993, and floodwaters at Canton, Missouri exceeded their "500-year" level in both 1993 and 2008. Statistical analysis of actual flood records shows that the recurrence statistics promulgated by the US Army Corps of Engineers (USACE, 2004) typically have less than a 1% chance of being realistic, which means that they have more than a 99% chance of being flat wrong. In fact, the USACE (2004) calculations are so far off that what is commonly called a "100-year" flood can be expected to occur every ten years or so (e.g., Criss, 2008, and refs. within). Given that the radwaste at West Lake Landfill will remain hazardous for many tens of thousands of years (Fig. 1), claims by EPA (2008) that this site is safe from flooding strain credulity.

The West Lake Landfill site is mapped by Missouri DNR as having high liquefaction potential, and as being near areas that have significant landslide potential (Hoffman, 1995). This means that both the landfill and any protective levees can slump or fail during an earthquake, during rainy periods, or during flooding, and would be especially vulnerable if such conditions coincided. During the wet period of May 1995, the northwest side of Area 2 of West Lake landfill underwent erosional scour, and sometime between 1973 and 1996, a "historical slope failure" spread radiologically-contaminated material from Area 2 onto several acres of the adjacent "Ford property" agricultural field (McLaren-Hart, 1996a, pp. 2.2, 3.3; Fig. 1.2). If such failures have happened, they cannot be imaginary.

WLLFOIA4312 - 001 - 0014466

5. Groundwater Contamination

The Missouri River floodplain is underlain by a productive and important alluvial aquifer, constituted of highly permeable, unconsolidated clastic sediments with a high, fluctuating groundwater table. This aquifer supplies hundreds of irrigation wells and numerous municipalities (e.g., Kelly 1996), and commonly has well yields of 100 to 3000 gpm (Miller and Appel, 1997). The water table in the alluvial aquifer is known to rapidly respond to the river stage as well as to the delivery of recent precipitation, with groundwater rapidly moving either toward or away from the river, depending on the river stage (e.g., Emmett and Jeffrey, 1968; Grannemann and Sharp, 1979; Criss and Criss, 2012). The USGS monitors several observation wells along the lower Missouri River, and these show that the elevation of the water table has varied by 10 to 40 feet within the last few years, depending on the particular site (USGS, 2013).

Because the landfill has no protective cap and no basal liner, any percolating waters can encounter radwaste and then move laterally and downward into the alluvial aquifer, or into the bedrock aquifer in the subjacent Mississippian limestone. Diagrams in McLaren-Hart (1996b; Fig. 3-29) clearly show groundwater in contact with landfill radwaste. Data in EMSI (2012) document that large-scale radionuclide migration in groundwater has occurred (see below).

6. Groundwater migration

NRC (1982, p. 22) concluded that "the buried ore residues are probably not soluble and are not moving off-site via ground water". However, NRC (1988, p. 14-15) subsequently concluded that "some low-level contamination of groundwater is occurring", and that "it is unclear whether the area's groundwater can be protected from onsite disposal".

In contrast, EPA (2008, p. 20) found that only a few of their samples of well water and surface water had Ra concentrations above the drinking water standard (MCL) of 5 pCi/l. Further they concluded that their results "generally show sporadic and isolated detections of a small number of contaminants at relatively low concentration levels," and that "These results are not indicative of on-site contaminant plumes, radial migration, or other forms of contiguous groundwater contamination that might be attributable to the landfill units being investigated."

EMSI (2012, p. iii) parrots EPA's statement about "sporadic and isolated detections …", yet abundant data in their report contradict it. For example, EMSI (2012, Fig. 5) measured a dissolved ^{226}Ra concentration of 29 pCi/l, 5 times the MCL, in piezometer PZ-101-SS, located about 500 feet south of the southern boundary of contaminated Area 1. Contrary to their claims (EMSI 2012; p. iii and p. 9), the potentiometric surface map in this report (Fig. 2; EMSI 2012) clearly shows that this piezometer is far downgradient, not "upgradient", of the water table in Area 1, so that the radiological contamination has migrated radially away from Area 1, as well as downward into the Mississippian bedrock aquifer. Abundant additional evidence for migration away from Areas 1 and 2 are provided in the dissolved Ra data shown on the available figures (EMSI, 2012; e.g., Figs. 8, 9).

EMSI (2012, p. 7) also argues that the hydraulic gradient in the alluvial aquifer is very flat, about 0.0004. However, these measurements are not typical as they were made in late July, 2012, in the middle of a protracted drought. Note that NRC (1988, p. 6) reported that the gradient was 0.005 in Nov. 1983 and March 1984, more than 10x greater than the atypical value reported by EMSI (2012). Moreover, numerous studies (e.g., Grannemann and Sharp, 1978) show that both the magnitude and

WLLFOIA4312 - 001 - 0014467

direction of this gradient rapidly change as the river level varies, which by itself indicates rapid groundwater migration.

EMSI (2012, p. 7) similarly underestimates the hydraulic conductivity of the alluvial aquifer, stating that their measurements indicate that it is only 8.5 to 85 ft/day. For comparison, Emmett and Jeffrey (1968) report a value of 400 ft/day for the hydraulic conductivity of this highly permeable aquifer, while the value determined by recent pump tests (NRC, 2010) are about 750 ft/day. Results in Criss and Criss (2012) for numerous sites along the lower Missouri River are consistent with the values of hydraulic conductivity reported by Emmett and Jeffrey (1968) and NRC (2010), but are clearly not consistent with the low values claimed by EMSI (2012).

The above considerations are highly germane to groundwater migration, because the groundwater velocity is related to the product of the hydraulic gradient and the hydraulic conductivity. Note that EMSI (2012) uses low values for both factors to claim that the "overall velocity of groundwater flow within the alluvium would be 0.0034 to 0.034 ft/day, or 1.2 to 12 ft/year. " Instead, the NRC data indicate that the velocity would be more than 100x faster than EMSI's upper limit. It should also be mentioned that these so-calculated "Darcy velocities" are about 4x slower than the actual microscopic velocity of the groundwater, because the real groundwater velocity also depends on the alluvium porosity.

In short, there is no scientific support for the conclusion by EPA (2008, p. 22) that " there is no contaminant plume further downgradient at some off-site location that could be attributable to the source material", nor for their consequent rationalization, "For this reason, off-site groundwater investigations were not undertaken as part of the RI." To the contrary, all available data show that radionuclides are actively migrating in groundwater, and that off-site groundwater investigations are absolutely necessary.

7. Background Radiation Levels

NRC (1982, p. 13) estimates that off-site background levels are 2 pCi/g for ^{226}Ra, and 0.2 pCi/m^2-s for the radon flux (p. 17). NRC (1982, Table 5) and NRC (1988, p. 9) report those levels as ~2.5 pCi/g for offsite soil, but a Rn flux almost 3x higher. NRC (1988, p. 10) estimates that the background level for gross alpha activity in water is 1.5 pCi/l.

For comparison, EMSI (2012, p. 13) measured ^{226}Ra levels as high as 29 pCi/l in groundwater located peripheral to the West Lake Landfill. They rationalize that these levels are natural, specifically that (p. 13) "the levels of radium detected in the monitoring wells reflect natural occurrences of radium." They further state that "Missouri generally, and the Site specifically, are located within the Ozark Plateau Cambro-Ordivician (MCOO) aquifer system," and cite Szabo et al. (2012) who found that this aquifer system has anomalously high Ra levels.

EMSI (2012) clearly does not understand that the Mississippian bedrock that immediately underlies West Lake Landfill is not part of the "Cambrian-Ordovician" aquifer, correctly spelled here. Moreover, the very top of the "Cambrian-Ordovician" aquifer, also known as the Ozark aquifer, lies about 1,000 feet below West Lake Landfill (e.g., Harrison, 1997). Moreover, the Ozark aquifer is generally separated from overlying Mississippian groundwater by an aquatard, or hydraulic barrier (e.g., Miller et al., 1974; Imes, 1988).

WLLFOIA4312 - 001 - 0014468

8) Assessment and Recommendations

My analysis of available data indicates the following:

1) The chemical and physical character of the radioactive material dumped at West Lake Landfill is unknown. Contrary to longstanding assertions, it appears than no more than a tiny fraction of the dumped radwaste could be "leached barium sulfate".

2) The radwaste will become considerably more radioactive for the next ~9000 years. Subsequently, that peak level will slowly attenuate, but radioactivity will not diminish to present-day levels for several hundred thousand years.

3) Remedial action is necessary, following sufficient study.

4) The site has several hydrologic and geologic risk factors that have been underestimated. A proximal underground fire magnifies the risk of radionuclide release, and underscores how unanticipated problems can affect hazardous sites containing materials that require isolation for thousands of years.

5) Available data prove that groundwaters have already interacted with radwaste.

6) Radiologically-contaminated groundwaters have moved substantial lateral distances away from the original areas where the radwaste was dumped, and also have entered subjacent Mississippian bedrock.

7) Regional analyses of gamma radiation, groundwater, sediment and rock are needed to establish meaningful background levels of radioactivity. Inappropriate comparisons in available reports have led to overstatement of local background levels and dismissal of obvious contamination as "natural".

8) Additional study of the site is needed. The character of the radioactive materials and processing wastes originally dumped at West Lake Landfill needs to be determined. Relevant, old chemical and radiological analyses of these materials probably exist, and physical samples may still exist. In lieu of these being found, radioactively-contaminated material from the landfill needs to be excavated and collected, processed by standard mineral separation techniques, and then analyzed and examined to determine the chemical, physical and radiological character of the separates of concern. Accurate determination of elemental ratios including Ra/Ba, Ra/U, Ba/U, Th/U, Ba/SO_4, etc. by ICP-MS and other modern techniques would clearly help. Groundwater analyses need to include major elements, physical parameters such as electrical conductivity, and stable isotope data so that radionuclides can be definitively traced to their sources by well-understood methods (e.g., Criss, 1999; Hasenmueller and Criss, 2013). It is not acceptable that so little is known about this radwaste after more than 30 years of "study". Regular monitoring of the levels and radionuclide contents of groundwater also need to be undertaken. Several dozen new monitoring sites must be developed to establish conditions at least 1000 feet away from the landfill boundaries, particularly north and northwest of Area 2, to establish the scale of groundwater contamination and migration.

EPA and the potentially responsible parties need to tend to the above concerns before making recommendations about remediation. They also need to familiarize themselves with abundant published literature that characterizes the hydrogeologic framework of east central Missouri and its

WLLFOIA4312 - 001 - 0014469

long recognized risk factors. Such effort would provide them with illuminating distinctions between the shallow groundwaters at West Lake Landfill and groundwater in the Ozark aquifer. The same reports would provide them with copious data about how shallow groundwaters along the lower Missouri River respond to river levels and interact with bedrock aquifers, and would correct their misconceptions about the direction that groundwaters flow in response to hydraulic gradients.

References

Criss, R.E. (1999) *Principles of Stable Isotope Distribution* , Oxford University Press, New York, 254 p.

Criss, R.E. and Shock, E.L. (2001) Flood enhancement through flood control. *Geology*, v. **29**, p. 875-878.

Criss, R.E. and Winston, W.E. (2008) Public Safety and faulty flood statistics. *Environmental Health Perspectives*, v. **116** #12, p. A516.

Criss, R.E., and Criss, E.M. (2011) Prediction of well levels in the alluvial aquifer along the lower Missouri River. *Ground Water,* v. **50** #4, p. 571-577.

Emmett, L.F. and Jeffery, H.G.. Reconnaissance of the ground-water resources of the Missouri River alluvium between St. Charles and Jefferson City, Missouri. Hydrologic Atlas HA 315, United States Geological Survey, 1968.

EMSI (2012) Groundwater Monitoring report, 2012 Additional Groundwater Sampling Event, West Lake Landfill Operable Unit-1. Engineering Management Support, Inc., 87 p.
EPA (1995) Air Emissions From Municipal Solid Waste Landfills -Background Information For Final Standards And Guidelines. EPA-453/R-94-021, 382 p.

EPA (2008) Record Of Decision, West Lake Landfill Site, Bridgeton, Missouri Operable Unit 1 U.S. Environmental Protection Agency Region 7 Kansas City, May 2008, 112 p.

Faure, G. 1986) *Principles of Isotope Geology*, John Wiley & Sons, New York, 589 p.

FEMA (1995) Landfill Fires: Their Magnitude, Characteristics and Mitigation . May 2002/FA-225, 26p.

Foss-Smith, Patrick (2010) Understanding Landfill Fires. Waste Management World, Aug. 2010. http://www.waste-management-world.com/articles/print/volume-11/issue-4/Features/understanding-landfill-fires.html

Grannemann, NG. and Sharp, J.M., Jr. (1979) Alluvial hydrogeology of the lower Missouri River Valley. *Journal of Hydrology*, v. **40**: p.85–99.

Harrison, R.W. (1997) Bedrock geologic map of the St. Louis 30'x60' quadrangle, Missouri and Illinois. U.S. Geological Survey Miscellaneous Investigation Series, Map I-2533.

WLLFOIA4312 - 001 - 0014470

Hasenmueller, E. A. and Criss, R. E. (2013) Multiple sources of boron in urban surface waters and groundwaters. *Science of the Total Environment* (STOTEN) V. **447**, 1 March 2013, p. 235-247.

Hoffman, David (1995) EQ Hazards Map of the St. Louis, Missouri Metro Area 1:100:000

Imes, J.L. (1988) Geohydrology and hydrogeochemistry of the Ozark Plateaus aquifer system. Regional Aquifer Systems of the United States, Swain, L.A. and Johnson, A.I., eds, AWRA Monograph Series 13, p. 165-178.

Kelly, B.P. (1996) Simulation of ground-water flow and contributing recharge areas in the Missouri River alluvial aquifer at Kansas City, Missouri and Kansas. Water-Resources Investigations Report 964250, United States Geological Survey, 1996. 93p

McLaren-Hart (1996b) Soil boring/Surface soil Investigation Report, West Lake Landfill Areas 1 & 2. Nov. 26, 1996.

Miller, J.A. and Appel, C.L. (1997) Groundwater atlas of the United States, segment 3, Kansas, Missouri, Nebraska. Hydrologic Investigations Atlas 730-D, United States Geological Survey.

Miller, D.E., Emmett, L.F., Skelton, J., Jeffery, H.G., and Barks, J.H. (1974) Water Resources of the St. Louis Area, Missouri. Missouri Geological Survey and Water Resources, Water Res. Rept. 30, 92 p.

NAP (1995) Safety of the high-level uranium ore residues at the Niagara Falls Storage Site, Lewiston, New York. National Academies Press. Avail. at: http://www.nap.edu/catalog.php?record_id=9161

NRC (1982) Radiological Survey of the West Lake Landfill, St. Louis County, Missouri. NUREG/CR-2722, 133 p.

NRC (1988) Radioactive material in the West Lake Landfill. NUREG-1308, 16 p.

NRC (2010) Combined license application documents for Callaway, unit 2 application. FSAR rev.2, sec.2.4. 602. http://www.nrc.gov/reactors/new-reactors/col/callaway/documents.html (accessed 7 2010).

Szabo, Z., dePaul, V.T., Fischer, J.M. Kraemer, T.F. and Jacobsen, E. (2012) Occurrence and geochemistry of radium in water from principal drinking-water aquifer systems of the United States. *Applied Geochemistry*, v. **27**, p. 729-752.

USACE 2004. U.S. Army Corps of Engineers, Upper Mississippi River System Flow Frequency Study: Final Report
http://www.mvr.usace.army.mil/pdw/pdf/FlowFrequency/flowfreq.htm
Also see: http://www2.mvr.usace.army.mil/flow_freq/flow_freq.cfm [accessed Feb. 2013]

USGS (2013) Groundwater data for the Nation.
http://waterdata.usgs.gov/nwis/dv/?referred_module=gw

Walker, F.W., Parrington, J.R. and Feiner, F. (1989) Chart of the Nuclides and Isotopes, 14th Ed., General Electric Co., 57 p.

WLLFOIA4312 - 001 - 0014471

Abbreviations Used in this Report

Ba	Barium
Bi	Bismuth
Pb	Lead
Po	Polonium
Ra	Radium
Rn	Radon
SO_4	Sulfate
Th	Thorium
U	Uranium
U_3O_8	Uranium oxide
VOCs	Volatile organic compounds

Ci	Curie
pCi/g	picoCuries per gram
pCi/l	picoCuries per liter
μR/hr	microRoentgen per hour
mR/hr	milliRoentgen per hr
MCL	Maximum Contaminant Level
ICP-MS	Inductively Coupled Plasma Mass Spectrometry

WLLFOIA4312 - 001 - 0014472