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Radiological Laboratory Sample Analysis Guide for Incidents of National Significance – Radionuclides in Water

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Radiological Laboratory Sample Analysis Guide for Incidents of National Significance — Radionuclides in Water

U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Radiation and Indoor Air
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Preface

The document describes the likely analytical decision paths that would be required by personnel at a radioanalytical laboratory following a radiological or nuclear incident, such as that caused by a terrorist attack. EPA's responsibilities, as outlined in the *National Response Plan Nuclear/ Radiological Incident Annex*, include response and recovery actions to detect and identify radioactive substances and to coordinate federal radiological monitoring and assessment activities. This document was developed to provide guidance to those radioanalytical laboratories that will support EPA's response and recovery actions following a radiological or nuclear Incident of National Significance (INS).

The need to ensure adequate laboratory infrastructure to support response and recovery actions following an INS has been recognized by a number of federal agencies. The Integrated Consortium of Laboratory Networks (ICLN), created through a memorandum of understanding in 2005 by ten federal agencies, consists of existing and emerging laboratory networks across the Federal Government. ICLN is designed to provide a national infrastructure with a coordinated and operational system of laboratory networks that provide timely, high quality, and interpretable results for early detection and effective consequence management of acts of terrorism and other events requiring an integrated laboratory response. It also designates responsible federal agencies (RFAs) to provide laboratory support across response phases for chemical, biological, and radiological agents. To meet its RFA responsibilities for environmental and drinking water samples, EPA is developing the Environmental Laboratory Response Network (eLRN). As an RFA for radiological agents, eLRN will be responsible for monitoring, surveillance, and remediation, and will share responsibility for incident response with the Department of Energy. As part of eLRN, EPA's Office of Radiation and Indoor Air is leading an initiative to ensure that sufficient environmental radioanalytical capability and competency exists across a core set of laboratories to carry out EPA's designated RFA responsibilities.

Three radioanalytical scenarios, responding to two different public health questions, address the immediate need to determine the concentration of known or unknown radionuclides in water. The scenarios are based upon the radionuclides that probably would be released by a radiological dispersion device or those that may be released intentionally into the drinking water supply. The first analytical scenario assesses whether water samples pose immediate threats to human health and warrant implementation of protective measures specific to radiation concerns. The second assesses whether specific water sources (samples) are potable based on current national drinking water standards. The third situation assumes that the radioactive contaminants are known, and a shortened version of the first two analytical scenarios is used to help expedite the analysis process. Use of established analytical schemes will increase the laboratory efficiency so that large numbers of samples can be analyzed in a timely manner. The use of the analytical schemes and the associated measurement quality objectives also will ensure that the radioanalytical data produced will be of known quality appropriate for the intended incident response decisions.

As with any technical endeavor, actual radioanalytical projects may require particular methods or techniques to meet specific measurement quality objectives. The document cannot address a complete catalog of analytical methodologies or potential radionuclides. Radiochemical methods to support response and recovery actions following a radiological or nuclear INS can be found in

Standardized Analytical Methods for Environmental Restoration following Homeland Security Events, Revision 3 (EPA 600-R-07-015).

Detailed guidance on recommended radioanalytical practices may be found in current editions of the *Multi-Agency Radiological Laboratory Analytical Protocols Manual* (MARLAP) and the *Multi-Agency Radiation Survey and Site Investigation Manual* (MARSSIM), both referenced in this document. EPA is developing companion documents for air and soil samples. Familiarity with Chapters 2 and 3 of MARLAP will be of significant benefit to the users of this guide.

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Acronyms, Abbreviations, Units, and Symbols

(Excluding chemical symbols and formulas)

α . . . . . alpha particle
α . . . . . probability of a Type I decision error
AAL . . . . . analytical action level
ADL . . . . . analytical decision level
AS . . . . . alpha spectrometry
β . . . . . beta particle
β . . . . . probability of a Type II decision error
Bq . . . . . becquerel (1 dps)
CERCLA . . . . Comprehensive Environmental Response, Compensation, and Liability Act of 1980 ("Superfund")
CFR . . . . . *Code of Federal Regulations*
cm . . . . . centimeter
cpm . . . . . counts per minute
d . . . . . day
DL . . . . . discrimination limit
DOE . . . . . United States Department of Energy
DP . . . . . decay product(s)
dpm . . . . . disintegration per minute
dps . . . . . disintegration per second
DQO . . . . . data quality objective
DRP . . . . . discrete radioactive particle
DWC . . . . . derived water concentration
e^- . . . . . electron
$E_{\beta max}$ . . . . . maximum energy of the beta-particle emission
EDD . . . . . electronic data deliverable
EPA . . . . . United States Environmental Protection Agency
γ . . . . . gamma ray
g . . . . . gram
Ge . . . . . germanium semiconductor
GM . . . . . Geiger-Muller detector
GP . . . . . gas proportional
GPC . . . . . gas proportional counting/counter
GS . . . . . gamma spectrometry
Gy . . . . . gray
h . . . . . hour
H_0 . . . . . null hypothesis
H_1 . . . . . alternate hypothesis
HPGe . . . . . high-purity germanium [detector]
IC . . . . . Incident Commander
ICC . . . . . Incident Command Center
IND . . . . . improvised nuclear device (i.e., a nuclear bomb)
INS . . . . . incident of national significance
keV . . . . . thousand electron volts
L . . . . . liter

LBGR . . . . . lower bound of the gray region
LEPD . . . . . low-energy photon detector
LS . . . . . liquid scintillation
LSC . . . . . liquid scintillation counter/counting
MARLAP . . . . *Multi-Agency Radiological Laboratory Analytical Protocols Manual*
MARSSIM . . . *Multi-Agency Radiation Survey and Site Investigation Manual*
MCL . . . . . maximum contaminant level
MeV . . . . . million electron volts
mg . . . . . milligram (10^{-3} g)
mL . . . . . milliliter (10^{-3} L)
mrem . . . . . millirem (10^{-3} rem)
µg . . . . . microgram (10^{-6} g)
µR . . . . . microroengten
MDC . . . . . minimum detectable concentration
min . . . . . minute
MQO . . . . . measurement quality objective
NaI(Tl) . . . . . thallium-activated sodium iodide detector
φ_{MR} . . . . . relative required method uncertainty
PAG . . . . . protective action guide
pCi . . . . . picocurie (10^{-12} Ci)
QA . . . . . quality assurance
QC . . . . . quality control
R . . . . . roentgten
rad . . . . . radiation absorbed dose
RDD . . . . . radiological dispersion device (i.e., “dirty bomb”)
RDL . . . . . required detection limit
REGe . . . . . reverse electrode germanium [detector]
rem . . . . . roentgen equivalent man
s . . . . . second
SDWA . . . . . Safe Drinking Water Act
SOP . . . . . standard operating procedure
Sv . . . . . sievert
TEDA . . . . . triethylenediamine
TEDE . . . . . total effective dose equivalent
UBGR . . . . . upper bound of the gray region
u_{MR} . . . . . required method uncertainty
y . . . . . year

Radiometric and General Unit Conversions

To Convert	To	Multiply by	To Convert	To	Multiply by
years (y)	seconds (s) minutes (min) hours (h) days (d)	3.16×10^{7} 5.26×10^{5} 8.77×10^{3} 3.65×10^{2}	s min h d	y	3.17×10^{-8} 1.90×10^{-6} 1.14×10^{-4} 2.74×10^{-3}
disintegrations per second (dps)	becquerels (Bq)	1	Bq	dps	1
Bq Bq/kg Bq/m^3 Bq/m^3	picocuries (pCi) pCi/g pCi/L Bq/L	27.0 2.70×10^{-2} 2.70×10^{-2} 10^{3}	pCi pCi/g pCi/L Bq/L	Bq Bq/kg Bq/m^3 Bq/m^3	3.70×10^{-2} 37.0 37.0 10^{-3}
microcuries per milliliter (µCi/mL)	pCi/L	10^{9}	pCi/L	µCi/mL	10^{-9}
disintegrations per minute (dpm)	µCi pCi	4.50×10^{-7} 4.50×10^{-1}	pCi	dpm	2.22
gallons (gal)	liters (L)	3.78	L	gal	0.264
gray (Gy)	rad	10^{2}	rad	Gy	10^{-2}
roentgen equivalent man (rem)	sievert (Sv)	10^{-2}	Sv	rem	10^{2}

Note: Traditional units are used throughout this document instead of SI units. Protective Action Guides (PAGs) and their derived concentrations appear in official documents in the traditional units and are in common usage. Conversion to SI units will be aided by the unit conversions in this table. Conversions are exact to three significant figures, consistent with their intended application.

I. INTRODUCTION

This guide deals with the analysis of water samples that may have been contaminated as the result of a radiological or nuclear event, such as a radiological dispersion device (RDD), improvised nuclear device (IND), or an intentional release of radioactive materials into a drinking water supply. In the event of a major incident that releases radioactive materials to the environment, EPA will turn to selected radioanalytical laboratories to support its response and recovery activities. In order to expedite sample analyses and data feedback, the laboratories will need guidance on EPA's expectations.

A response to a radiation release to the environment likely will occur in three phases: "early," "intermediate," and "recovery." Each phase of an incident response will require different and distinct radioanalytical resources to address the different consequences, priorities, and requirements of each phase. Some of the more important radioanalytical laboratory resources germane to incident response and recovery consist of radionuclide identification and quantification capability, sample load capacity, sample processing turnaround time, quality of analytical data, and data transfer capability.

The early phase begins at the initial event and lasts for three or four days, during which data are scarce, and pre-planned dispersion models are used. During this phase, responders are primarily concerned with evacuating people, sheltering them in place, or restricting use of specific water supplies. The purpose of the actions and evaluations taken during the early phase is to minimize exposure and to prevent acute health effects. The Protective Action Guides (PAGs) for radiological emergencies require evacuation of a population if the projected short-term total effective radiation dose equivalent[1] (TEDE) exceeds 5 rem.[2] The nominal trigger for sheltering is 1–5 rem over four days (projected avoided total effective dose). The radioanalytical resource requirements (field or fixed laboratory) for this early phase may vary significantly depending on the timeframe, source term radionuclide and the extent of the contamination.

The intermediate phase begins when no more radiation releases are expected, and the source term contamination radionuclides have been qualitatively identified. In this phase, radionuclide concentrations, extent of the contaminated zone, and matrices (air, water, soil) required for analysis may not be well defined. The radioanalytical resources needed will depend on the radionuclide analytical action levels (AAL) developed for the various media important to human exposure. The AAL may change depending upon the stage of the event, the appropriate PAGs, or risk values. The radionuclide derived water concentrations (DWCs) are based on the PAGs or risk values. For the intermediate phase, PAGs have been established to limit the projected radiation doses for different exposure periods; not to exceed 2-rem TEDE over the first year, 500-mrem TEDE during the second year, or 5 rem over the next 50 years (including the first and second years of the incident). In addition, radionuclide concentration limits for food and water as regulated by the Food and Drug Administration and EPA would be applicable.

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[1]The sum of the effective dose equivalent (for external exposure) and the committed effective dose equivalent (for internal exposure). TEDE is expressed in units of sievert (Sv) or rem.

[2]The common unit for the effective or "equivalent" dose of radiation received by a living organism, equal to the actual dose (in rads) multiplied by a factor representing the danger of the radiation. "rem" stands for "roentgen equivalent man," meaning that it measures the biological effects of ionizing radiation in humans. One rem is equal to 0.01 Sv.

The final, or "recovery," phase occurs as part of a radiological incident site- or drinking-water-supply remediation effort. During this final phase, when site- or drinking-water-supply characterization and remediation cleanup effectiveness is determined, there is a potential for more extensive radiochemical analyses at the lowest radionuclide concentrations. Applicable drinking water regulations for radionuclides (40 CFR Parts 9, 141, 142) may be used during this phase.

During all phases of an incident response, radioanalytical resources are needed for identifying the radionuclide source terms, quantification of the radionuclides in a variety of media, and the gross radiation screening of samples for prioritization of sample processing or for information related to the general level of contamination. This guide has been developed to provide the Incident Commander (IC) and the laboratories selected to analyze samples during an incident with a logical processing scheme to prioritize sample processing in relation to the radionuclide derived water concentrations corresponding to established PAGs or Maximum Contaminant Levels (MCLs) under the Safe Drinking Water Act.

A. Objectives

This document is intended to assist those analytical laboratories that will be called upon to provide rapid support to Agency personnel following a radiological or nuclear incident. Because EPA recognizes that in the immediate and intermediate period following such a release, there may not be sufficient time for the Incident Command Center (ICC) to coordinate and communicate complete data quality objectives, measurement quality objectives, and analytical priorities to the laboratory, this document will enable laboratories to proceed with a consistent approach to developing and reporting appropriate data suitable for the anticipated use.

The ultimate purpose of the screening process described in this guide is to ensure that public health is protected. The recommendations in this guide are based upon EPA's PAGs and applicable drinking water regulations for radionuclides (40 CFR Parts 9, 141, and 142, *National Primary Drinking Water Regulations; Radionuclides*; Final Rule. *Federal Register* 65:76707-76753, December 7, 2000).

This document presents a series of three analytical scenarios to aid laboratories in establishing priorities for analyzing samples received during the response to a radiological or nuclear incident. The following table summarizes the relevant responsibilities of the IC and the laboratory manager during such a response.

Information Provided...	Sample Priority	Method Uncertainty	Miscellaneous MQOs	Reporting (Results and Anomalies)	Analyte Selection	Turnaround Time Compliance	Procedure Selection
By:	IC	IC	IC	Lab	IC	Lab	Lab
To:	Lab	Lab	Lab	IC	Lab	IC	IC

One of the key objectives in this document is to explain the responsibilities indicated above in terms of analytical processes. While the IC should provide the necessary information (analytes, matrices, measurement quality objectives) that define the scope of the laboratory's processing requirements and results, the laboratory should ensure that the methods used have been validated and will meet the required measurement quality objectives (MQOs) and the required turnaround time. It is possible that immediately following such an event, especially when MQOs may not have been established or provided, laboratories may receive samples without complete documentation or direction. In such

cases, laboratories may follow the procedures and examples in this document, and be confident that their results should provide reasonable and consistent results.

This document is not meant to replace any field monitoring decisions on sample prioritization. It is intended as a guide on how to establish priorities for samples received at the laboratory at different times throughout the response, and it should provide to the IC the basis for understanding the nature and limitations of the data received from the laboratories. Familiarity with Chapters 2 and 3 of MARLAP will be of significant benefit to the users of this guide.

B. Scope and Radiological Scenarios

Radiological incidents can be subdivided into three phases: early (onset of the event to about Day 4), intermediate (about Day 4 to about Day 30), and recovery (beyond about Day 30). This guide concentrates on the time from the end of the early phase, through the intermediate phase and into the recovery phase. During the early phase, analytical priorities need to address the protection of the public and field personnel due to potentially high levels of radioactivity, and to provide for *qualitative* identification of radionuclides. During the intermediate phase, the radionuclides and matrices of concern are known *qualitatively*, and the *quantitative* levels suitable for making decisions based on analytical action levels need to be rapidly determined. The phase of an incident where this document will find its greatest utility is early in the intermediate phase through the end of the recovery phase. Laboratories performing analyses must focus on rapid turnaround of sample results and optimized sample analysis so that the initial qualitative aspects and concentrations related to the appropriate AALs can be determined quickly. During the recovery phase, the screening techniques used for samples will be of less significance because the radionuclides from the event are likely to have been characterized already. This is represented by the lower portions of the flow-charts, which address analyses of specific radionuclides. Potable water supplies will be evaluated against MCLs during this recovery phase.

Three distinct radioanalytical scenarios are presented for water potentially contaminated with radionuclides. The first two assume that the radionuclides are unknown.

- The first scenario is a water supply, surface, or groundwater source highly contaminated with an unknown quantity of yet unidentified radionuclides.

- The second scenario requires that the laboratory determine whether a water source from the affected areas and unknown source term is safe to drink.

- The third scenario, where the radionuclides have been identified, occurs later during the early or intermediate phases, and the laboratory need not waste analytical processing time trying to identify which radionuclides are present. The decision tree focuses on establishing the priority for processing samples based on the gross concentration screening values for the specific radionuclides.

In Radioanalytical Scenario 1, the identity of the radionuclides and potential concentrations are unknown. This is most likely to occur during the early phase of the event. The laboratory's priority is to identify all the radionuclides present and their concentrations in the water sources sampled.

The need to identify safe sources of drinking water (Radioanalytical Scenario 2) will occur later in

the intermediate phase and into the recovery phase. Once all the radionuclides are identified, Radioanalytical Scenario 3 may be used for either scenario, depending upon the direction of the IC.

These scenarios may be applicable in different phases of the event, although as was previously indicated, Scenario 1 is usually the early phase and Scenario 2 is late-intermediate to recovery phase. Figure 1 depicts how these three radioanalytical scenarios relate to the response team's needs for sample prioritization.

In the third scenario, the radionuclides have been identified. This situation can arise during any of the phases, so while Figure 1 depicts Scenario 3 occurring during the later intermediate phase, Scenario 3 could occur earlier. The laboratory can save time by analyzing samples for its specific radionuclides, after it has had a gross screen to determine sample-processing priority based on its gross concentrations. Formal evaluation of other naturally occurring radionuclides may be necessary when assessing the water as a potential drinking water source.

As introduced earlier, PAGs establish radiation dose limits applicable to different phases of an incident response. The drinking water PAG (expressed as a numerical dose level) indicates a level of exposure at which protective action should be taken to prevent, reduce, or limit a person's radiation dose during a radiological incident. The derived water concentration (DWC) is the *concentration* of a radionuclide in water corresponding to the PAG dose and is used to facilitate the application of PAGs in the radioanalytical laboratory. For example, the concentration of ^{137}Cs in drinking water corresponding to the 500-mrem PAG is 5.8×10^{4} pCi/L.

Similarly, radionuclide DWCs corresponding to other specific dose or risk value may be calculated and applied as required. The term "analytical action level" (AAL) will be used as a general term denoting the radionuclide concentration at which action must be taken by incident responders.

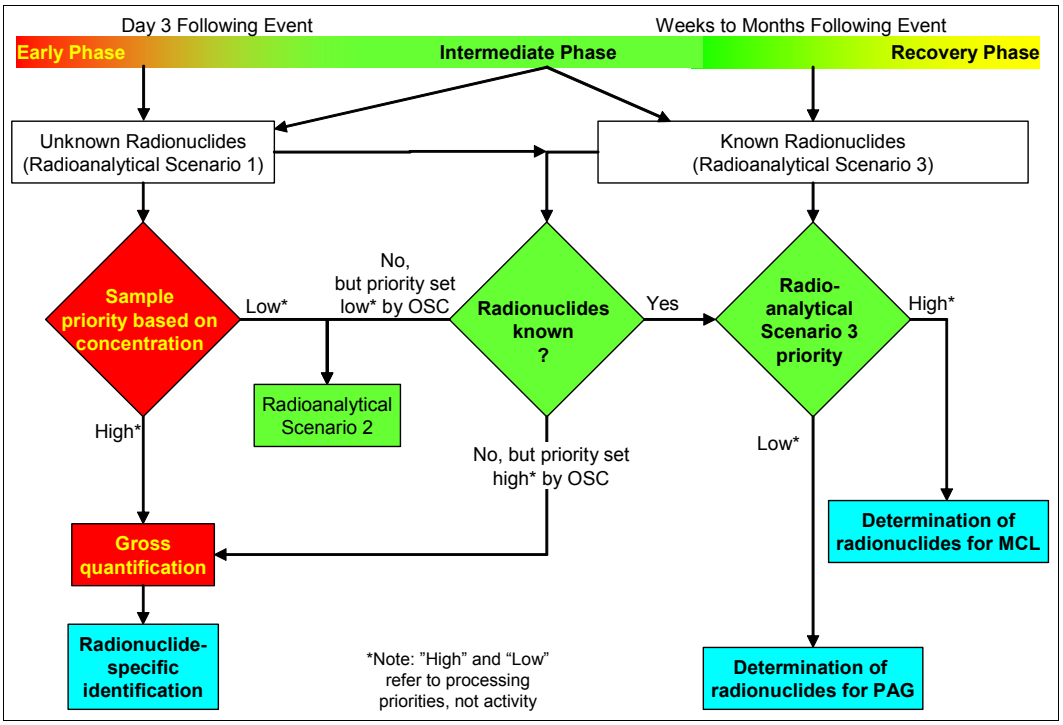

Figure 1 – Water Sample Scenarios and Response Phases

Decisions related to the processing and prioritization of specific samples will be made by laboratory personnel at the laboratory by comparing the results of radioanalytical measurements to "analytical decision level" (ADL) concentrations. Whenever the measured analyte concentration equals or exceeds the applicable ADL concentration, it will be concluded that the AAL (PAG or risk factor) has been exceeded.

When applied to prioritizing samples for processing, the ADL concentrations are always less than the corresponding AAL values by an interval calculated to provide statistical confidence when deciding whether the corresponding AAL has or has not been exceeded. The magnitude of this interval corresponds to the maximum uncertainty that would be consistent with acceptable decision error rates established during the data quality objectives (DQO)/MQO process.[1] In this process, the MQO of greatest significance is the required method uncertainty, u_{MR}. An example of a dose and its corresponding AAL, ADL, and u_{MR} is shown here for ^{226}Ra (based on tolerable Type I and Type II error rates; see details in Appendix VI):

Measurement Type	Dose (mrem)	AAL[2] (pCi/L)	ADL (pCi/L)	u_{MR} (pCi/L)
Screening[3]	100	180	90	54
Radionuclide-specific[4]	100	180	130	22

Laboratories will perform both gross activity measurements and radionuclide-specific measurements during an incident. Because different DQOs and MQOs are applicable to different types of measurements, different u_{MR} and corresponding ADL values are provided for screening and radionuclide-specific analyses. The default values for u_{MR} and corresponding ADL for screening and radionuclide-specific determinations presented in Tables 5A, 5B, 6A, and 6B provide laboratories with a starting point for developing protocols and systems for incident response activities. It is anticipated that in the case of an incident, specific DQOs and MQOs may be developed by Agency personnel to reflect the specific nature and concerns of the incident and provided to the laboratory.

Decisions related to water quality suitable for drinking are based on specific regulatory values based on the Safe Drinking Water Act (SDWA). In this case, specific values for the Maximum Contaminant Level (MCL) and the Required Detection Level (RDL) are applicable for each radionuclide, as well as gross α and β (see Tables 7A and 7B). If more than one beta- or gamma-emitting radionuclide is present, the "sum of fractions" rule applies. This is best illustrated in the example found in Appendix II, Scenario 1, Step 15. The "sum of fractions" rule does not apply to alpha-emitting radionuclides.

The flow diagrams and corresponding numbered notes and data tables depict the analytical processing suggested for rapid response and consistency. In keeping with concepts of the *Multi-Agency Radiological Laboratory Analytical Protocols (MARLAP) Manual*, this guide does not specify analytical methods. A performance-based approach for the selection of appropriate analytical methods by the laboratory will be used to achieve MQOs specified by this document and the IC.

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[1]Appendix VI provides the derivation and detailed discussion of MQOs, required method uncertainties, and ADLs.

[2]See Appendix VI, Table 10A.

[3]Tables 5A and 5B in Appendix I summarize default ADLs and u_{MR} for screening measurements.

[4]Tables 6A and 6B in Appendix I summarize default ADLs and u_{MR} for radionuclide-specific measurements.

Radiochemical methods to support response and recovery actions following a radiological or nuclear INS can be found in *Standardized Analytical Methods for Environmental Restoration following Homeland Security Events, Revision 3* (EPA 600-R-07-015).

MQOs are statements of performance objectives or requirements for selected method performance characteristics. Method performance characteristics include the method uncertainty, the method's detection capability, the method's quantification capability, the method's range, the method's specificity, and the method's ruggedness. An example MQO for the method uncertainty at a specified concentration, such as the AAL, could be:

> "A method uncertainty of 50 pCi/L or less is required for ^{241}Am analysis at the 100-mrem AAL of 400 pCi/L."

The MQOs and any other analytical requirements serve as the basis for the laboratory's selection of a method under a performance-based approach. The laboratory should have performance data to demonstrate the method's ability to achieve the project-specific MQOs. Method validation and continued acceptable method performance assessments are essential to the performance-based approach to method selection.

This document presents a default set of MQOs. Actual MQOs, however, always will depend upon events and may need to be modified by the IC to better address a particular event. However, in order to have an analytical approach in place to address a variety of incident scenarios, the identified decision points in the accompanying flow diagrams refer to the default MQOs—primarily in the form of required method uncertainties—for analyzing the radionuclides of concern. For example, at most decision points in the diagrams where a quantitative value is given, a u_{MR} at that AAL is identified in the notes and the tables. The u_{MR} values are identified in Tables 5A, 5B, 6A, and 6B of Appendix I. Appendix VI describes the methodology used to establish the required method uncertainties identified in these tables. It is important to note that the ADL values specified in Appendix I are less than the PAGs or AALs stated in Appendix VI, Tables 10A and 10B, by the statistical factors identified in Appendix VI. In a few cases, an MQO in the form of a Required Detection Limit is used. These decision points have action limits (MCLs and RDLs) that are specified by regulation (i.e., the Safe Drinking Water Act). These are specifically identified in Tables 7A and 7B in Appendix I. In these instances, the measured value need only be less than the MCL to be within the limits of the regulation, and the sample-specific detection limit need only be less than or equal to the RDL.

Once the appropriate method has been selected, then based on the required method uncertainty or required detection limit, the laboratory can select the proper aliquant size, counting time and other parameters to meet the MQOs in the most efficient manner.

C. Analytical Response Time

Decisions regarding the extent of contamination in surface and groundwater supplies will need to be made in a timely manner. Approximate times required for laboratory processing of these samples and finalizing the sample results are shown in Appendix V. This identifies the workflow for making qualitative and quantitative measurements of high-activity contaminated water samples (Radioanalytical Scenario 1). In addition, results of the sample radioanalytical measurements needs to be communicated promptly by the laboratory to the IC so that decisions regarding movement of

population, sheltering, and additional sampling can be made.

D. Implementation

It may be necessary for laboratories to incorporate key aspects of this document into their standard operating procedures. For example, the gross screening process will require specific standards and response factors for each of the instruments used by the laboratory. This could be a departure from the laboratory's current screening practice because the activity levels, sample geometries, and matrices may be significantly different from what the laboratory normally experiences.

Laboratories should become proficient with these procedures because they could be asked to respond to analytical requests in hours rather than weeks. Thus, laboratory personnel should become familiar with the recommendations and procedures, and laboratories should consider both training and actual "drills" or exercises where analytical scenarios and samples are tested during a controlled scenario. The frequency and depth of these exercises will be at the discretion of the laboratory management.

Laboratory personnel also should be cross-trained in different areas of the incident response functions. This will help to ensure sample analysis continuity throughout the length of the incident response.

Certain values are identified in the tables in this document for presumptive AALs, which may be relied upon in the absence of explicit action levels received from the Incident Command Center, so that the laboratory may begin to process samples promptly. However, these values may change based on the needs of the particular event. MQOs will be stipulated by the IC and should be communicated to the laboratory as early as possible so that analysis can meet project objectives.

E. References

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Approved *Standard Methods for the Examination of Water and Wastewater*, required for analyses under Radioanalytical Scenario 2, include the following. Analysis of the radionuclides discussed in the following section with procedures from other standard organizations may be acceptable (see 40 CFR 141.25 for alternative methods).

- 7110 Gross Alpha and Gross Beta Radioactivity (Total, Suspended, and Dissolved) (*3 methods*)
- 7120 Gamma-Emitting Radionuclides (*2 methods*)
- 7500-3H Tritium (*2 methods*)
- 7500-Cs Radioactive Cesium (*2 methods*)
- 7500-I Radioactive Iodine (*2 methods*)
- 7500-Ra Radium (*5 methods*)
- 7500-Sr Total Radioactive Strontium and Strontium-90 (*2 methods*)
- 7500-U Uranium (*3 methods*)

II. RADIONUCLIDES

Table 1 lists some of the radionuclides that are believed to be accessible and possibly could be used in a radiological dispersion device (RDD)—or "dirty bomb"—or used to contaminate a drinking water supply, and which are addressed in this report.

This list is specifically for a RDD event and the major (noninclusive) dose-related radionuclides that might be formed from the detonation of an improvised nuclear device (IND). In the case of a IND, numerous short- and long-lived fission product radionuclides will be present, requiring proper identification and quantification. Several of the radionuclides on the list have progeny that will coexist with the parents. Thus, if ^{228}Th is found, ^{224}Ra also would be present (although it is not listed). Several different radionuclides may be present even if only one RDD is used.

TABLE 1 – Radionuclides of Concern

Radionuclides Alpha Emitters		Radionuclides Beta/Gamma Emitters	
Am-241	Ra-226	Ac-227†	Mo-99†
Cm-242	Th-228	Ce-141*	P-32*
Cm-243	Th-230	Ce-144‡	Pd-103*
Cm-244	Th-232	Co-57*	Pu-241
Np-237	U-234	Co-60*	Ra-228
Po-210*	U-235	Cs-134*	Ru-103†
Pu-238	U-238	Cs-137§	Ru-106†
Pu-239	U-Nat	H-3*	Se-75*
Pu-240		I-125*	Sr-89*
		I-129†	Sr-90†
		I-131*	Tc-99*
		Ir-192*	

* No radioactive progeny or progeny not analytically useful.
† Radioactive progeny with short half-lives, and the progeny may be used as part of the detection method for the parent.
‡ Radioactive progeny not used for quantification, only screening.
§ Radioactive progeny used for quantification only, not screening.

III. DISCUSSION

In order to illustrate the typical decisions and actions to be taken by a laboratory for each scenario, examples of the three scenarios using theoretical samples and measurement results are provided in Appendices II, III, and IV. These examples represent only three of many different possible permutations, however, and should not be construed as limiting. Each example is keyed back to the steps in its respective diagram and notes.

These scenarios assume that the time period from taking the sample to the actual beginning of the analysis by the laboratory will be short (under one day). Therefore, samples received by the laboratory will not be preserved, nor will they have been filtered. Sample filtration generally should not be performed until the extent of contamination and the radionuclide identity(ies) are known. The final decision on this must be communicated to the laboratory by the IC based on the project MQOs. Should it be necessary to delay analysis for any sample for more than two days, the sample should be preserved according to the analysis protocols to be determined.

For the three scenarios discussed in this guide, it is assumed that field personnel have performed some type of radiation detection survey of the samples prior to sending them to the laboratory. If appropriate, field personnel may determine which samples are to be submitted first to the laboratory based on these survey results. The laboratory's surveys and analyses of the samples are not intended to confirm the field survey results.

Only qualified laboratories using validated radioanalytical methods (see EPA 2007b and MARLAP, Chapter 6) should be used in order to process samples in a timely and effective manner. These laboratories will have the necessary radioanalytical capability and sample-processing capacity to conduct the required gross screening and radionuclide-specific analyses defined for the radioanalytical scenarios. This guide recommends the following analytical process flow.

1. General screening based on total radiation emitted from the sample.
2. Screening based on type of radiation emitted (i.e., alpha, beta, or gamma).
3. Specific analytical techniques applied after screening indicates the most significant activities.

This sequence is used for screening in the diagrams for each radioanalytical scenario. Each decision point in the flow diagram relates to an AAL (based on a PAG DWC, regulation, or risk-based DWC) that is part of the overall analytical process. The flow diagrams for the three radioanalytical scenarios (Figures 2, 3, and 4) use simplified process-control shapes: diamonds represent decision choices, and rectangles are action or information steps. The numerical limits in the diamonds of the flow diagrams are ADLs. Many of the flow diagram shapes have numbers keyed to the notes immediately following the respective figures. Most shapes are color-coded to reflect the highest priority analytical flow path (red), intermediate (next important) flow path (green), or the lowest priority flow path (yellow) based on the time needed to return the required analytical results to the IC. The accompanying numbered notes are color-coded in the same fashion, as are the examples in Appendices II, III, and IV. Consequently, it is highly advisable to study the flow paths in color, as a black-and-white version may be confusing or ambiguous.

The screening techniques outlined in the first steps of the flowcharts assume that the laboratory maintains the necessary instrumentation and can perform the initial gross sample screening (at or immediately subsequent to sample receipt) functions identified below:

- Micro-R meters for evaluating radiation exposures and doses on low-activity samples.
- Dose-rate meters capable of detecting gamma-beta exposures and doses.
- Hand-held gross alpha frisker for assessing the alpha count rate on sample contact.
- Survey meters with appropriate alpha, beta, and gamma detector probes can be used to determine whether samples exceed the maximum dose rate that can be handled or analyzed at the laboratory.

The instrument used for gross screening analysis (mostly for γ radiation) should be calibrated (pCi/net dose rate) with a ^{137}Cs source of appropriate geometry.

The laboratory also should have the instrumentation to perform radionuclide-specific analyses (e.g., high-purity germanium [HPGe] detectors for gamma and ion implanted silicon detectors for alpha spectrometry). Some of the radionuclides listed in Table 1 on page 9 (e.g., ^{103}Pd) can be detected only with a specific type of gamma-ray detector because of their low gamma-ray emission energy (60 keV is the usual lower energy for many HPGe calibrations).

Each numbered box has associated with it a note that provides additional detail for that particular part of the process. Clarification is also provided in these notes as to when parallel paths of analysis should be followed to help expedite the processing of samples.

Table 12 (Appendix VI) provides estimated counting times for LSC and GPC and the minimum detectable concentration (MDC) that can be achieved by screening a small sample aliquant for gross alpha and beta activity. The values are based on typical detector efficiency and background values for two methods, gas proportional and liquid scintillation counting. Laboratories should prepare their own MDC tables using their preferred detection method as part of their standard operating procedures (SOPs). Laboratories also should determine (in advance) whether their individual analytical protocols will need to be revised to accommodate this process.

The number of samples that will be analyzed, and their level of contamination, will be significantly higher than normal samples. Laboratories must also consider the following:

- Separate sets of procedures for sample handling and storage.
- Increasing the frequency of detector background analyses.
- Increasing the frequency of QC checks.
- Consider adjusting the QC check activity level to more closely align with the activity of the anticipated samples.
- Increasing the frequency of contamination assessments (i.e., smears/swipes) on working surfaces in the laboratory.
- Separate protocols for personnel protective equipment.
- Separate protocols for personnel and sample radiation monitoring.
- Separate storage location for high-activity samples or a large group of samples, which would increase laboratory background for detectors or personnel. This storage location may need additional shielding or be sited so as not to affect operations.

It should be noted that modern radioanalytical procedures in the United States address low ambient concentrations of environmental radionuclides normally encountered during the past 30 years. With the detonation of an RDD or IND involving radionuclides with radioactive progeny, it is possible that the radioactive equilibria involved with these progeny may have been established (depending

on the time between creation of the radionuclide source to detonation or the time of detonation to sampling, or both). This means that not only will there be considerably higher concentration of the parent but of each of the progeny. Furthermore, if multiple radionuclides are involved, the cross-contamination factor during separations must be minimized, a phenomenon that current day analysts may not have previously experienced. A specific example of such a phenomenon would be the elimination of ^{140}Ba during the ^{90}Sr separation process. Many processing schemes in today's laboratories do not account for this step because many samples are collected over a period of weeks to months and provided to laboratories as composites. Routine turnaround time for ^{90}Sr analysis is 30 days. Thus, even if the 12-day ^{140}Ba radionuclide is present, it would have decayed significantly by the time the laboratory receives the sample for analysis.

IV. CROSSWALK of Data Values

The values corresponding to different terms referred to in this document are located in the tables listed below:

TABLE 2 – Crosswalk of PAG, SDWA Limits, AAL, ADL, and u_{MR} Values

	SDWA Required Limits	AAL	ADL	u_{MR}
500 mrem/100 mrem (Screening)	Tables 10A and 10B (PAGs)	—	Tables 5A and 5B	Tables 5A and 5B
100 mrem (Radionuclide Specific)	—	Tables 10A and 10B (PAGs)	Tables 6A and 6B	Tables 6A and 6B
SDWA MCL Values	Tables 7A and 7B	—	—	—
SDWA RDL Values	Tables 7A and 7B	—	—	—
DQO and MQO Derivations	—	—	Tables 9A, 9B, 11A, and 11B	Tables 9A, 9B, 11A and 11B
Estimated Counting time for MDC (based on screening analysis)	Table 12	—	—	—

EPA's Response Protocol Toolbox (EPA, 2003) provides additional recommendations concerning planning and threat management, site characterization and sampling, and sample analysis to assist utilities and state and local agencies. If laboratory protocols for normal or routine situations cannot ensure that the DQOs and MQOs are achievable with the laboratory's SOPs under emergency conditions, then a separate set of SOPs for emergency conditions will need to be developed.

V. RADIOANALYTICAL SCENARIO 1 (Identifying Samples with Highest Activities)

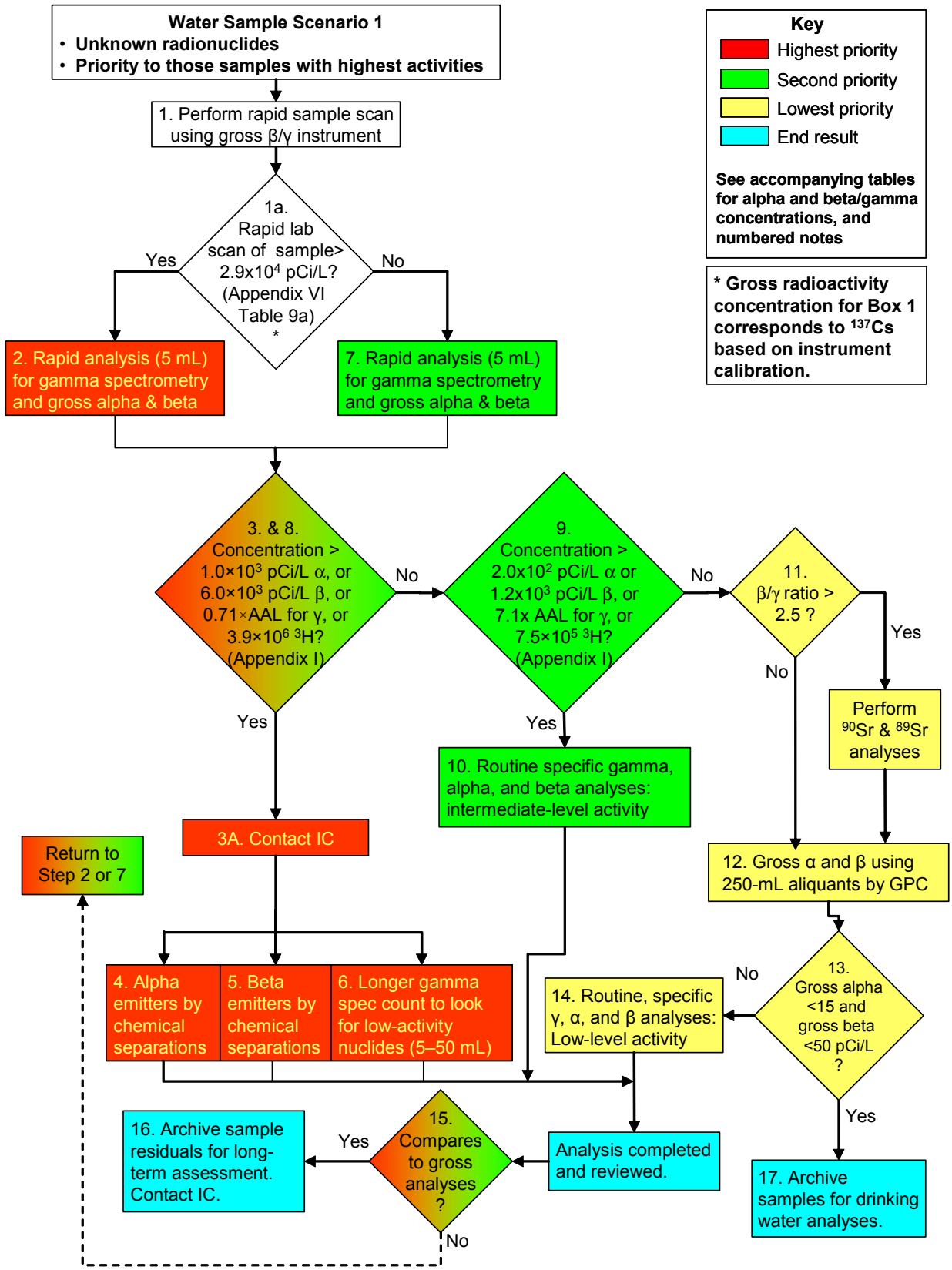

Figure 2 – Water Scenario 1 Analytical Flow

Notes to Scenario 1: Contaminating Radionuclides Unknown
Purpose: Priority to Those Samples with Highest Activities

Highest priority samples are all analyzed first. Only after an analytical step or procedure has been completed for the highest priority samples should lower priority samples be addressed. The samples may arrive over several days; those with the highest priority are always to be analyzed first. Lower priority samples (those following the green and yellow flow paths on this chart) may need to be stored for several days until the highest priority samples have been analyzed.

Many of the flow diagram shapes are color-coded to reflect the highest priority analytical flow path (red), intermediate (next important) flow path (green), or the lowest priority flow path (yellow) based on the time needed to return the required analytical results to the IC. The accompanying numbered notes are color-coded in the same fashion, as are the examples in Appendix II. It is highly advisable to study the flow paths in color, as a black-and-white printing may be confusing or ambiguous.

1. Analysis at this point is to assess if the 500-mrem AAL[1] values are exceeded by measurement of the sample's total gross radioactivity (concentration) with hand-held survey instruments. These might include a survey meter or Geiger-Muller (GM) counter with appropriately calibrated beta and gamma detector probes or a micro-roentgen meter (gamma only).[2] This step would most likely be performed with the sample container, unopened, leaving the determination of α ADLs to the next step. Unless the identification of the radionuclide contamination is known, the hand-held survey instrument should be calibrated using a ^{137}Cs source that would replicate the sample container geometry. The subsequent measurement should be capable of identifying a concentration from zero to 5.8×10^4 pCi/L, which is the 500-mrem AAL for ^{137}Cs. The ADL for this screening analysis is 2.9×10^4 pCi/L when applied to unknown radionuclides (see Appendix VI, Table 9A, on page 57). If the identification of the radionuclide(s) is known, the Analytical Detection Level (based on the AAL for the radionuclide listed for the 500-mrem value) is to be used (see Appendix I, Tables 5A and 5B). For survey instruments having an exposure rate readout, the instruments should be calibrated in terms of pCi/L per exposure unit readout for each container geometry expected and for the nuclide of interest, if known (^{137}Cs for unidentified nuclides).

Some laboratories may also use a calibrated NaI(Tl) detector to assess gross γ activity level (using an integrated spectrum technique) and relate this measurement to a gross or radionuclide-specific γ ADL.

Some gamma-emitting nuclides may not be detected at their ADLs if the sensitivity of the instrument used is inadequate. Tritium will not be detected, and beta-emitting radionuclides

[1] Depending on the time of the response, a 2-rem PAG may be applicable. If so, values for this may be obtained by scaling the PAGs and the ADLs by multiplying their corresponding 100-mrem values by 20. Thus the 2-rem PAG and ADL for ^{137}Cs would be 2.4×10^5 and 1.2×10^5, respectively.

[2] Some manufacturers have developed kits that include the survey meter plus an alpha–beta–gamma pancake GM detector and a NaI gamma detector.

that do not emit γ- or X-rays may not be detected depending on the window thickness of the detector.

The initial results of these measurements need to be checked against the information in the chain-of-custody form. Communication of preliminary findings to the IC may be very valuable in helping the IC determine the areas that may need additional samples. This feedback also will reinforce the priorities assigned to each sample and further enhance decision making.

1a. If the gross activity scan yields a value greater than 2.9×10^4 pCi/L, go to Step 2 (red path). Otherwise, go to Step 7 (green path).

> NOTE: The gross radioactivity measurements under Note 2 are evaluated against the ADLs listed in Table 5B for ^{241}Am, ^{90}Sr and ^{60}Co, respectively, at the 500-mrem level. These are not the lowest ADL values for all radionuclides. Thus, no conclusions about the presence or absence of other radionuclides should be made at this point in the analytical process.

2. If the gross α, β, or γ activities of these samples indicate that an AAL may have been exceeded (i.e., the sample activity is greater than one of these ADL values: 1.0×10^3 alpha, or 6.0×10^3 β, or [0.71×AAL] for an individual γ pCi/L[1]), then these analyses have the highest priority. Rapid analytical techniques, using a 5-mL sample aliquant, for α and β by either liquid scintillation counting (LSC)[2] or gas proportional counting (GPC) should be done to assess the individual levels of these components of the mixture. Additionally, a rapid gamma isotopic analysis needs to be performed using a HPGe detector. Note that, dependent upon the type of instrument used, the count time for some analyses may be shorter with LSC than with GPC. Screening for radionuclides such as $^{125/129/131}$I by GPC may need to be carefully performed to prevent loss of radionuclide analyte due to volatilization during sample evaporation.

Gamma isotopic analysis is performed with a high-purity germanium (HPGe) detector to identify the major γ emitters. Analysis should be made on the original sample container or on an aliquant as small as 20 mL in a standardized counting geometry. The γ isotopic analysis (original sample container or 20-mL aliquant) of Steps 2 and 7 using a HPGe detector and a counting time ≥10 minutes should be satisfactory for achieving the required method uncertainties for the γ-emitting radionuclides in Table 5B (counting time will meet both the 500- and 100-mrem ADL values).

Tritium, a potential contaminant, will not be detected by either of the gross analysis scans unless LSC is used to determine gross beta. If GPC is used for gross beta analysis, a separate aliquant of the sample will need to be analyzed for tritium. Tritium analysis should be

[1]These values are based on the ADL values for ^{241}Am and ^{90}Sr, respectively. The assumption is that the detection device is calibrated with ^{137}Cs and will yield the most representative gross activity measurement at this point in the screening process. The gamma ADL is 0.71×AAL value for any individual gamma ray emitter.

[2] LSC screening of samples typically is preferred over GPC because sample preparation of a 5-mL aliquant is much simpler, less time-consuming, and minimizes the risk of contamination. In addition, for the same counting time, LSC screening for this AAL has a better detection capability compared to GPC.

performed during this stage of the analytical process. The ADL for tritium at this stage is 3.9×10^6 pCi/L.

3. Once the rapid analyses have been performed, the data should be reviewed to verify that the screening ADL concentrations have or have not been exceeded:

- 1.0×10^3 α pCi/L corresponding to ^{241}Am
- 6.0×10^3 β pCi/L corresponding to ^{90}Sr
- the γ-specific concentrations listed
- 3.9×10^6 for ^{3}H

(See the pCi/L values for other individual α- and β-emitting radionuclides listed in Tables 5A and 5B).

This is particularly important for α emitters, because the previous step was the first measurement of alpha radioactivity. Note that if exceeding the ADLs is not confirmed by at least one of the three analyses, the sample analysis reverts to the second priority analysis path.

Sample analysis prioritization will be based upon which ADL is exceeded. The γ analysis may help to assess which of the specific radionuclide analyses needs to be pursued with the highest priority. For example, if gross α activity exceeds the ADL and the γ radionuclides identified account for the observed gross β activity, for which no individual β- or γ-emitting radionuclide ADL has been exceeded, priority would then shift to specific α emitters. Note in Table 5B that ^{57}Co, ^{75}Se,^{103}Pd, and ^{125}I are γ-emitting nuclides only (these radionuclides decay via electron capture) and have no contribution to the results of a gross β analysis.

In a different example, the gross β indicates an ADL has been exceeded, but the gross α ADL was not exceeded. In this case, the β emitter analyses would take priority along with gamma spectrometry analysis. These together would identify the specific β components of the sample. The α analysis could be relegated to a lower priority flow path.

Some additional information may be obtained from the γ-ray analysis of those radionuclides that are principally α or β emitters and have very low abundance γ rays. These types of radionuclides may be qualitatively identified in a short count (see Table 3, page 20). Qualitative identification of γ rays from those types of radionuclides may aid the laboratory in sample analysis prioritization.

High levels of β activity with no significant specific γ component may warrant an additional GPC screening technique by using mass absorbers[1] to assess the β-particle energy. A sample volume greater than 5 mL may be required to effectively assess the range of the particles by

[1]A technique that has been used successfully to determine the energy of beta-only emitters is to measure the range of the beta particles in a pure material ("Feather analysis"). The ranges of beta particles in several pure materials (such as aluminum) have already been established. The units of thickness are expressed as areal density, or mg/cm^2. A set of aluminum absorbers of varying thickness is used, and the activity versus the absorber thickness is plotted on a semi-log scale. The linear portion of this curve is then extrapolated to find the "zero" activity thickness. This is then related to the $E_{\beta max}$ of the beta particle, which will be characteristic for a particular radionuclide. A discussion of this technique can be found in *Principles of Radioisotope Methodology*, 3rd Edition, G.D. Chase and J.L. Rabinowitz, Burgess (Minneapolis) 1967.

this method. This could minimize time spent on searching for the radionuclide (see Table 4, page 21).

Following Step 3, the highest activity samples that exceed the 1.0×10^3 or 6.0×10^3 pCi/L ADL screening levels (gross α or β), ^{3}H, or specific ADL γ-emitting radionuclide concentrations, respectively, should be analyzed through Steps 4, 5, and 6 as quickly as possible. This will enable the laboratory to recalibrate its gross screening methods for those radionuclides actually found in the sample, which in turn will improve the accuracy of the gross screening techniques in assessing whether ADLs have been exceeded for subsequent samples. This also means that subsequent samples from the same location may be able to follow Radioanalytical Scenario 3 (page 28).

3a. The existence of samples exceeding the 500-mrem ADLs should be communicated to the IC as soon as possible.

> NOTE: Steps 4, 5, and 6 may be done concurrently based on the gross analysis results.

4. Chemical separation for specific α radionuclides commences if the gross α concentration exceeds the ADL (see Table 5A, page 32). Certain α emitters also emit γ rays or have γ-emitting decay products that may be identified in Step 3. The γ results can be used to determine which α emitter analyses need not be performed immediately. For example, lack of a significant 59 keV peak in the γ spectrum would indicate that an analysis for ^{241}Am does not have to be performed. If the project manager does not specify the sequence of analyses, laboratory personnel should use their best professional judgment, based on the characteristics of the samples, to determine the order of processing the samples so that the results are obtained in the most efficient manner.

5. Chemical separations to be performed for specific β radionuclides, not identifiable via gamma spectrometry, include ^{3}H, ^{32}P, ^{241}Pu, ^{90}Sr, and ^{89}Sr. If the project manager does not specify the sequence of analyses, laboratory personnel should use their best professional judgment, based on the characteristics of the samples, to determine the order of processing the samples so that the results are obtained in the most efficient manner.

6. The initial gamma spectrometry results will have identified high activity samples that may provide insight as to which α- or β-only emitters are present. This longer count (compared to Step 7) and optional larger sample size should focus on lower-intensity γ-ray lines from additional radionuclides. When counting is completed, the analyst should ensure that newly identified γ-rays are from different radionuclides and not just low intensity lines from the predominant γ emitters.

> NOTE: Once radionuclides have been identified, gross screening methods should be recalibrated to the radionuclides of interest, and the laboratory may follow the flowchart for Radioanalytical Scenario 3.

7. If the initial gross screening method (Step 1) does not indicate a radioactivity greater than the ADLs, gross α and β analyses using a 5-mL sample and a counting time of about 30 minutes should be performed to verify that these ADLs have not been exceeded. The γ

isotopic analysis (original sample container or 5-mL aliquant) of Steps 2 and 7 using a HPGe detector and a counting time less than 60 minutes may have a detection limit needed to quantify radionuclides at concentrations corresponding to the 500- or 100-mrem ADLs. If not, the sample should be counted longer.

Tritium is a potential contaminant that will not be detected by either of the gross analysis screens unless LSC is used to determine gross beta. If GPC is used for gross beta analysis, a separate aliquant of the sample will need to be analyzed for tritium by LSC. Tritium analysis should be performed during this stage of the analytical process. The ADL for tritium at this stage in the analytical process is 7.5×10^5 pCi/L.

8. Here the results from screening analyses performed in Step 7 are compared to the 500-mrem ADLs from Tables 5A and 5B (α 1.0×10^3 or β 6.0×10^3), <u>or</u> specific γ-emitting radionuclide ADL concentrations, respectively. If the screening concentrations are greater than these ADLs, a high priority would be established to analyze the samples for specific radionuclides in Steps 4, 5, or 6. If the screening results of Step 7 do not exceed the ADLs, then the question in Step 9 is evaluated.

9. Does the gross or specific radionuclide concentration exceed the corresponding (α 200 or β 1.2×10^3)* <u>or</u> specific γ-emitting (3.3×10^3 for ^{60}Co) radionuclide 100-mrem ADL concentrations, respectively? If "yes," proceed immediately with subsequent analyses. The status of samples exceeding the 100-mrem ADLs should be communicated to the IC. If "no," go to Step 11.

> NOTE: "*" gross concentrations noted above correspond to the 100-mrem ADL values for ^{241}Am and ^{90}Sr, respectively, listed in Tables 5A and 5B. These are not the lowest concentrations for all radionuclides, and decisions about the presence of other radionuclides should not be made until radionuclide-specific analyses have been performed.

10. Use a routine method that can provide analytical results within about one day. Sample size and counting time will need to be increased to verify screening levels and to quantify those radionuclides whose individual concentrations are below their corresponding 100-mrem ADL values listed in Tables 5A and 5B on pages 32 and 33 (see notes for Steps 4, 5, and 6 for other information on specific radionuclide analyses).

Calculate the sum of the ratios (individual nuclide concentration/100-mrem AAL are in Tables 10A and 10B, page 59) of all radionuclide concentrations above their respective RDL values (Tables 7A and 7B, page 36). If the summed value exceeds unity, then the 100-mrem AAL has been exceeded even though an individual value <u>does not</u> exceed the ADL (see example calculation in footnote 2 on page 41).

If the IC does not specify the sequence of analyses, laboratory personnel should use their best professional judgment, based on the radiological characteristics of the samples and in order of highest to lowest concentration, to determine the order to process the samples to produce expeditious results.

11. A β/γ ratio >2.5 (i.e., ratio of gross β to gross γ) indicates that ^{90}Sr or ^{89}Sr may be a signifi-

cant contaminant. Although this decision falls into the low-priority path, this analysis should be done first for the low-priority samples because of the dose significance of ^{90}Sr and the time required to do this analysis. Note that for the higher priority flow path, determination of strontium would be done in parallel with other analyses, so the urgency of its analysis does not need to be emphasized. Sufficient activity of the sample is necessary to have a statistically significant β/γ ratio. The summed individual γ activities obtained from the HPGe detector from the printout would need to be applied for this calculation.

12. A GPC gross α and β analysis of a larger sample (250 mL) and a longer counting time is warranted. These analyses will determine if either of the MCL values for drinking water (15 α pCi/L or 50 β pCi/L) has been exceeded. Range determination of β-particle energy (see footnote on page 16) may be very effective with this 250-mL sample residue. This would help to further refine which β-only emitter is present at the highest concentration and deserves the priority analysis.

13. Determine if any gross α, β, or γ sample concentration exceeds the concentration corresponding to the screening MCL. For alpha emitters, this is 15 pCi/L and for beta emitters, this is 50 pCi/L. The status of any samples exceeding Safe Drinking Water Act standards should be communicated to the field coordinator.

14. Routine low-level analyses including total radiostrontium should be performed if not already done. If total radiostrontium results are greater than the ADL, use classical techniques to identify activities of ^{89}Sr and ^{90}Sr separately. A longer count time γ isotopic analysis should be completed first. This will assist in the identification of α or β emitters, which may have low abundance gamma rays. Additionally, if the γ emitters are parent isotopes for other radionuclides, this will direct the analyst on which other analyses should be performed first. Sample size, counting time, and turnaround times shall be adjusted based on the laboratory's SOPs for water-compliance monitoring (see notes for Steps 4, 5, and 6 for other information on specific radionuclide analyses).

If the gross α concentration is between 5 and 15 pCi/L, α-specific radionuclide analysis is required to identify the radionuclides, including ^{226}Ra. If the gross α concentration is less than 5 pCi/L, the sample should be analyzed for ^{228}Ra and ^{226}Ra, and by gamma spectrometry to verify that there are no low-activity γ emitters present.

15. When the high and intermediate priority radionuclide-specific analyses are completed, verify that no major nuclide has been missed: the sum of the individual nuclide concentrations (excluding tritium if screening measurement was made by GPC) is approximately equivalent to the gross activity concentration (a rule of thumb is within a range of about half to twice the gross value). This check will ensure that the sum of the measurements compares reasonably to the total measured gross activity. Activity concentrations due to decay products should be included in the verification. If not yet verified, the sum of the ratios (individual β- and γ-emitter radionuclide concentration/100-mrem AAL are in Table 10B) of all radionuclide concentrations above their corresponding RDL value (Table 7B) must be calculated. If the summed value exceeds unity, then the 500-mrem or 100-mrem AAL has been exceeded, even though an individual radionuclide activity value <u>does not</u> exceed the respective ADL (see example calculation in Appendix II, Scenario I, Step 15).

16. All samples should be archived for long-term or follow-up analyses. Those samples having radionuclide concentrations exceeding concentrations for the 100-mrem ADLs should be checked for preservation and stored for potential future analysis.

The IC should be notified with specific results for samples and radionuclide concentrations.

17. Archive samples for drinking water analyses. See Tables 7A and 7B for drinking water MCLs and their required detection limits (RDLs).

Additional Points:

Analysts should recognize that when performing gross α or gross β analysis by evaporation of a sample, a significant loss of volatile radionuclides (such as tritium and iodine) will occur. Following this initial screening technique, the absence of any volatile radionuclides may need to be verified, depending upon the nature of the event.

Certain α- and β-emitting radionuclides have γ rays that are not used normally for analysis of those radionuclides, and may not necessarily be identified in gamma spectrometry software. The combination of gamma-ray abundance and half-life makes the gamma ray of little utility unless there is a significant mass of the material or the sample is counted for a long time. It is recommended that a separate library for incident response samples be created that has these γ rays. Table 3 provides some examples.

TABLE 3 – Radionuclides with Low-Abundance Gamma Rays Not Usually Used For Their Analysis

Radionuclide	**^{89}Sr**	**^{90}Y**	**^{129}I**	**^{210}Po**	**^{226}Ra**		**^{228}Th**
Principal Decay	β^-	β^-	β^-	α	α		α
Gamma, keV	909	1761	40 (32 X-ray)*	80.3	186 (262)*		84
Abundance, %	9.5×10^{-4}	1.1×10^{-2}	7.5 (92.5)*	1.1×10^{-3}	3.3 (5×10^{-3})*		1.21
Radionuclide	**^{232}Th**	**^{235}U**	**^{237}Np**	**^{238}Pu**	**^{239}Pu**	**^{240}Pu**	**^{241}Am**
Principal Decay	α	α	α	α	α	α	α
Gamma, keV	911 (from ^{228}Ac)	185.7	86.5	55.3	112.9	54.3	59.5
Abundance, %	27.2	54	12.6	4.7×10^{-2}	4.8×10^{-2}	5.2×10^{-2}	35.7
Radionuclide	**^{241}Pu**	**^{242}Pu**	**^{243}Cm**				
Principal Decay	β^-	α	α				
Gamma, KeV	149	44.9	278				
Abundance, %	1.9×10^{-4}	4.2×10^{-2}	14				

* Values in parentheses represent the next most abundant gamma ray.

These gamma rays can be used for qualitative identification of these radionuclides. Their presence in the gamma-ray spectrum should direct the analyst to perform chemical separations followed by alpha- or beta-specific detection.

Aluminum absorbers can be used to qualitatively identify the presence of radionuclides based on penetrating ability. Thus, if an aluminum absorber of 6.5 mg/cm^2 is used, and the measured activity is reduced to background, one could qualitatively state that the beta particle energy of the radionuclide is < 0.067 MeV. Conversely, if the absorber has little effect on the count rate, it can

be stated that the beta particle energy is >0.067 MeV. Table 4 identifies some beta-only emitters with their energies and range in aluminum absorbers.

TABLE 4 – Beta "Only" Emitters

Radionuclide	**^{241}Pu**	**^{63}Ni**	**^{129}I**	**^{35}S**	**^{99}Tc**	**^{32}P**	**^{90}Sr/^{90}Y**
Maximum Beta Energy, MeV	0.021	0.067	0.150	0.167	0.294	1.711	(0.546)/2.28 [1]
Range [2] in Aluminum, mg/cm^2 for $E_{\beta max}$	0.8	6.5	27	32	75	800	1,100

Notes:

[1] It may be assumed that ^{90}Sr/^{90}Y will be in secular equilibrium by the time any analysis is started. Thus, the 2.28 MeV beta particle of ^{90}Y will be present.

[2] U.S. Department of Health, Education and Welfare (HEW). 1970. *Radiological Health Handbook*, p.123.

VI. RADIOANALYTICAL SCENARIO 2 (Identifying Uncontaminated Drinking Water)

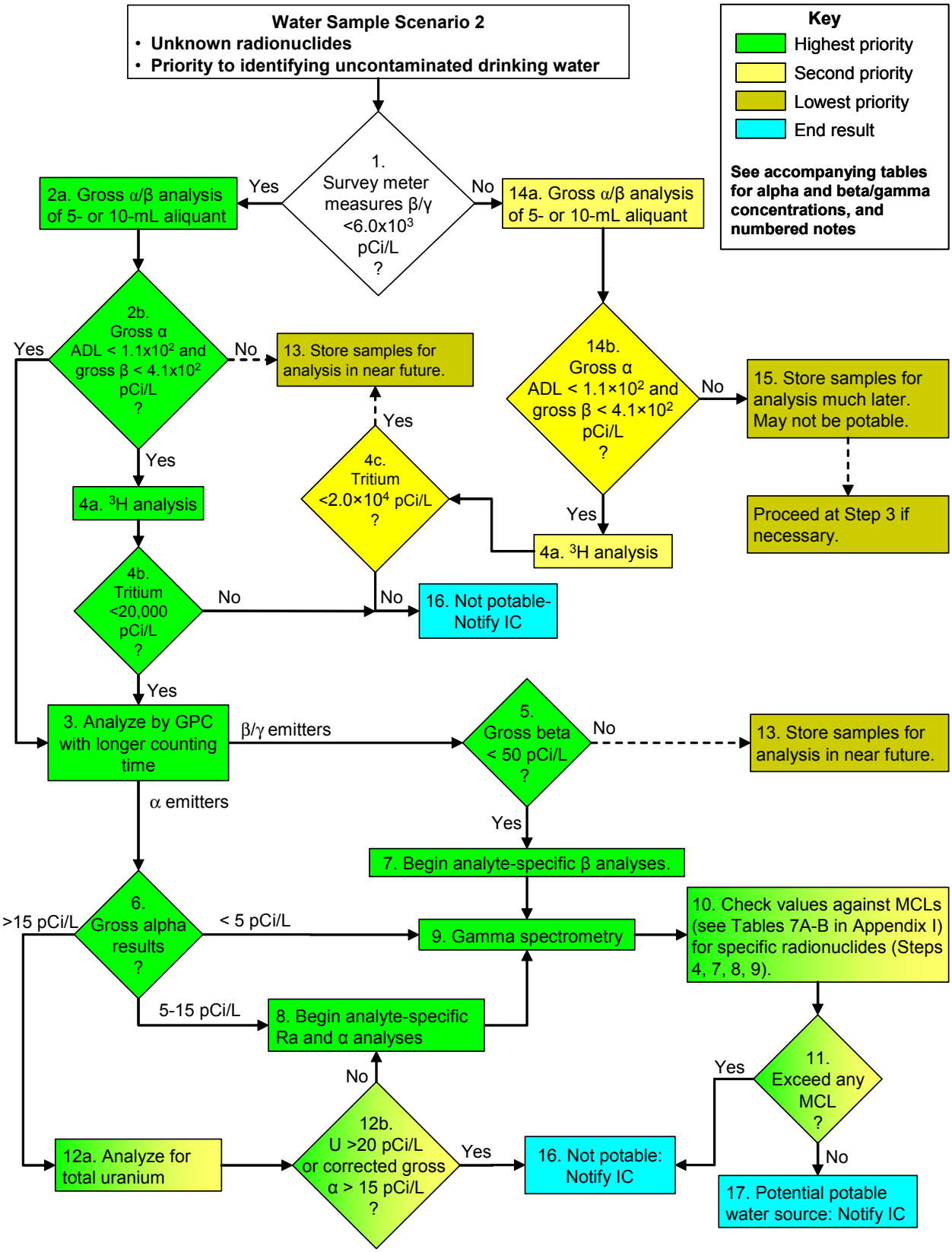

Figure 3 – Water Scenario 2 Analytical Flow

Notes for Scenario 2: Contaminating Radionuclides Unknown
Purpose: Rapid Identification of a Potable Water Source

Highest priority samples are all analyzed first. Only after an analytical step or procedure has been completed for the highest priority samples should lower priority samples be addressed. he samples may arrive over several days; analysis for those with the highest priority are always started first. Lower priority samples (those following the green and yellow flow paths on this chart) may need to be stored for several days until the highest priority samples have been analyzed. The samples with the highest priority in this instance will be the ones with the lowest activity. Gross α and β, and all analyses done to assess MCL values, must use standard methods approved for drinking water (page 9). This scenario assumes that the sources being analyzed have already been used as potable water sources.

Many of the flow diagram shapes are color-coded to reflect the highest priority analytical flow path (green), intermediate (next important) flow path (yellow), or the lowest priority flow path (olive brown) based on the time needed to return the required analytical results to the IC. The accompanying numbered notes are color-coded in the same fashion, as are the examples in Appendix III. It is highly advisable to study the flow paths in color, as a black-and-white printing may be confusing or ambiguous.

1. Screening with a hand-held survey instrument is to be performed as a contact reading on the outside of the sample container. The purpose of this screen is to eliminate quickly those samples that are obviously contaminated and thus may not be used as a drinking water source. Appropriate instruments might include a survey meter or Geiger-Muller counter with calibrated beta and gamma detector probes or a micro-roentgen meter (gamma only),[1] using a ^{137}Cs source geometry that would replicate the sample container geometry. The calibration measurement should be capable of identifying a concentration down to 6.0×10^3 pCi/L, which is half of the 100-mrem AAL for ^{137}Cs. Laboratories will need to develop instrument-specific calibration SOPs, which include the use of a mock sample container with a radionuclide source.

NOTE: The next steps use screening techniques. The MDCs are used as AALs. These values are based on those routinely achievable using the count times and volumes noted in Table 12 of Appendix VI.

2a. Gross alpha and gross beta screening measurements may be performed using a liquid scintillation counter (LSC)[2] or a gas proportional counter (GPC). For LSC, a 5- to 10-mL sample is mixed with a liquid scintillation cocktail in a LSC vial and counted for approximately 10 minutes. For GPC, a 5- to 10-mL sample is deposited on a planchet,

[1] Some manufacturers have developed kits that include the survey meter plus an alpha–beta–gamma pancake GM detector and a NaI gamma detector.

[2] LSC screening of samples typically is preferred over GPC because sample preparation of a 5-mL aliquant is much simpler, less time-consuming, and avoids possible contamination.

evaporated, and then counted for approximately 30 minutes. Note that, dependent upon the type of instrument used, the count time for some analyses may be shorter with LSC than with GPC. The total mass of evaporated residue for GPC analysis may prevent processing a full 500 mL aliquant. In these cases, a smaller volume and longer count time will be required.

The ADLs for this part of the analysis are based on the AAL being considered MDC values. The ADL values are 110 pCi/L gross α and 410 pCi/L gross β concentration (see Table 11A in Appendix VI). Table 12 in Appendix VI shows that the MDC values (210 pCi/L and 820 pCi/L) can be achieved with a 10-minute count of a 5-mL sample. Volumes and count times may be adjusted based on laboratory-specific instrumentation.

Screening for radionuclides such as $^{125/129/131}$I will not be able to be performed by GPC unless the samples are carefully prepared to prevent loss of radioiodines due to volatilization. Furthermore, radionuclides that decay by electron capture (such as ^{57}Co, ^{75}Se, ^{103}Pd) may not be able to be screened using GPC. If any of these electron-capture radionuclides are present, analysis using a low-energy photon detector (LEPD) or a specific separation scheme for each will be required.

Tritium cannot be screened using GPC techniques, because it will most likely be present as a tritiated water molecule. LSC should be used routinely for tritium analysis because of tritium's very low electron energy and its likely presence as part of a water molecule. For these reasons, tritium has a special status. If GPC analysis, and both alpha and beta analyses are less than the ADLs, Steps 4a and 4b must be performed. If LSC analysis is used and both alpha and beta analyses are less than the ADLs, proceed directly with Step 3.

2b. A concentration less than the ADL for this part of the analysis—110 pCi/L gross α and 410 pCi/L gross β—will identify the samples most likely to have radionuclide concentrations that are below the Maximum Contaminant Levels (MCLs) for natural radionuclides, as well as anthropogenic radionuclides.

In subsequent steps, it will be necessary to show that gross α < 15 pCi/L and gross β < 50 pCi/L (40 CFR Parts 9, 141, and 142, *National Primary Drinking Water Regulations; Radionuclides*; Final Rule. *Federal Register* 65:76707-76753, December 7, 2000).

If the results of either the gross alpha or beta analysis are greater than the ADLs for this step (which are based on the MDCs in Table 12), the sample should be checked for preservation and stored for analysis at a later time, to assess the presence of other radionuclides.

3. The gross alpha and beta results should be compared to specific limits from the Safe Drinking Water Act (Steps 5 and 6). The analyses for gross alpha and beta at these levels will require a larger sample volume and longer counting times. Gross α and β analysis by GPC is a requirement of the SDWA.

> NOTE: Steps 3 and 4a (4a only required when GPC analysis is done) should be done in parallel to expedite the decision for further analyses.

4a. Samples for tritium analysis may need to be either distilled or passed through an ion exchange resin if the gross beta results indicate significant counts above background (this could be due to naturally occurring radionuclides and still be less than MCLs). If tritium is present above the MCL of 20,000 pCi/L, the water source is not suitable for long-term use as drinking water.

4b. If the high priority sample tritium result is <20,000 pCi/L, a fresh sample aliquant (~ 4 L, portions of which will be used for separate analyses) should be analyzed for gamma, beta, and alpha emitting radionuclides (Steps 7, 8, and 9). If tritium concentration is > 20,000 pCi/L, the water is not a suitable drinking water source (Step 16).

4c. If tritium concentration of the low priority sample is >20,000 pCi/L, the water supply is not suitable as a drinking water source (Step 16). If tritium concentration is < 20,000 pCi/L, preserve the sample for future analyses (Step 13).

5. Analysis for specific beta emitters (Step 7) will be performed if the gross beta activity is less than 50 pCi/L. Methods used for specific beta emitters should be able to distinguish among the various isotopes of a specific element. Gross beta activity greater than 50 pCi/L means the source may not be suitable as a long-term drinking water supply. The sample should be checked for preservation and stored for analysis at a later date (Step 13).

6. Gross alpha analysis will need to distinguish among three different levels. Gross alpha activity between 15 and 35 pCi/L shall be analyzed for uranium contributions (Step 12). The uranium result is subtracted from the gross alpha result to determine gross alpha exclusive of uranium.

If gross alpha is between 5 and 15 pCi/L, alpha-specific radionuclide analysis is required to identify the radionuclides, with ^{228}Ra and ^{226}Ra taking priority. After or at the same time as these analyses, gamma spectrometry should be performed to assess presence of any gamma emitters.

Finally, if the gross alpha is less than 5 pCi/L, the sample should be analyzed for ^{228}Ra and ^{226}Ra, and by gamma spectrometry to verify that there are no low-activity gamma emitters present. The project manager may request additional radionuclide-specific analysis for man-made alpha emitters.

7. Chemical separation to be performed for pure β-emitting radionuclides not identifiable using gamma spectrometry include—but are not limited to— ^{3}H (Step 4), ^{90}Sr, ^{89}Sr, ^{99}Tc, ^{241}Pu, and ^{32}P. Sr-90 and ^{89}Sr would have the highest priority if project management guidance is not provided. This step is done in parallel with Step 9.

8. Gross alpha activity between the detection limit and 15 pCi/L may indicate presence of anthropogenic alpha emitters or naturally occurring radium radionuclides. The exact nature of the activity should be verified, because these samples are the result of contamination. Samples should be analyzed for ^{228}Ra and ^{226}Ra.

9. Samples for gamma spectrometry analysis should be counted long enough to meet the ^{134}Cs RDL of 10 pCi/L. The count time is dependent on the sample size, background, and detector

efficiency (this will be a laboratory-specific counting time; 1-3 hours is an approximate value). The software library should include lines for the predominant gammas of all products in the U and Th natural decay series as well as any anthropogenic radionuclide with a half-life of greater than 1 day. The purpose of including these naturally occurring gamma-ray peaks in the library is to ensure complete identification of all gamma rays. Due to differential solubilities of the progeny of U, Th, and Ra, no assumptions or predictions can be made regarding the presence of the parents unless specific radiochemical separations are performed. Gamma analyses should be performed in parallel with the alpha- and beta-specific analyses. This step is done in parallel with Step 7.

10. Here the results from analyses performed in Steps 4a, 7, 8, and 9 are compared to their respective MCLs (Tables 7A and 7B, Appendix I).

11. If any radionuclide exceeds its MCL, the source should not be considered potable (Step 16). For beta emitters, the sum of the ratios (individual nuclide concentration/MCL value) of all concentrations greater than the RDL values must be calculated. If the sum of the fractions of all β and γ-emitting radionuclides present exceeds 1.0, the water source is not potable.

12a. If gross alpha analysis in Step 6 is greater than 15 pCi/L, then perform analysis for total uranium (i.e, total uranium present on a mass basis).

12b. If the total uranium concentration is less than 20 pCi/L (30 µg/L or 30 ppb), and the corrected gross alpha activity (Gross alpha - total uranium) > 15 pCi/L, go to Step 8 and begin ^{226}Ra and ^{228}Ra analyses and any other alpha analyses requested by the IC. If the total uranium concentration is greater than 20 pCi/L, the water source cannot be used as a potable water supply (Step 16).

13. It is possible that the source may be acceptable for drinking water once radionuclide-specific analyses are performed. This path has a secondary priority. These samples should be checked to assess whether or not preservation, using acids or other appropriate chemical, has been performed. If not preserved, preservation appropriate to the analyte(s) should be made and the sample stored for potential analysis. Any decision to conduct further analyses or to dispose sample(s) should be made by the IC.

NOTE: The values in Step 14b correspond to the ADL values in Table 11A of Appendix VI.

14a. Samples that are greater than 6.0×10^3 pCi/L using the survey meter screening method may contain naturally occurring radionuclides but will not be potable. Analyze an aliquant of the sample by gross alpha and beta analysis.

14b. If the results of either the gross alpha or beta analysis[1] are greater than the ADLs, the sample should be preserved for analysis at a later time. It will not be acceptable as a drinking water source, but more detailed analysis may subsequently be required. If the gross alpha and gross beta analyses are both less than 110 pCi/L gross α and 410 pCi/L gross β, tritium analysis

[1] LSC screening of samples typically is preferred over GPC because sample preparation of a 5-mL aliquant is much simpler, less time-consuming, and avoids possible contamination.

should be performed later (Step 4a of the yellow path).

15. Those samples that exceed the ADLs established for Steps 2a and 2b should be checked for preservation and stored until all other water sources have been analyzed and found acceptable or not acceptable. Specific radionuclide analyses may determine that the water source is acceptable.

16. The water supply is not suitable as a drinking water source. At least one analysis or the sum of the fractions of the beta emitters has exceeded the MCL for drinking water for that radionuclide.

VII. RADIOANALYTICAL SCENARIO 3 (Contaminating Radionuclides are Known)

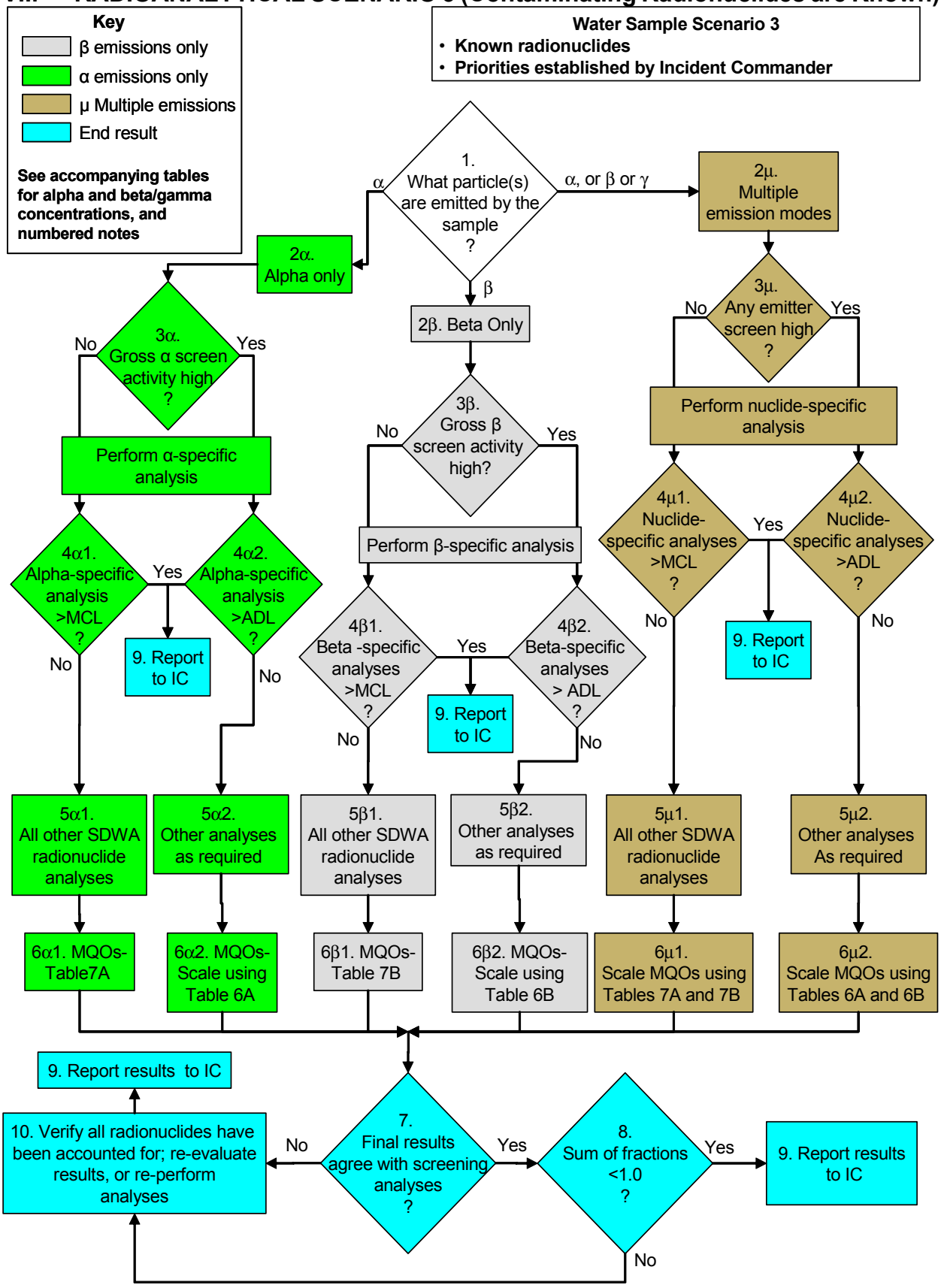

Figure 4 – Water Scenario 3 Analytical Flow

Notes for Scenario 3: **Contaminating Radionuclides Known**
Purpose: **Support the Specific Needs of the IC**

For this scenario, "α" and "β" designate paths to be followed (and their associated notes) when samples received from the field contain radionuclides that emit only alpha or beta particles, respectively, and "μ" (indicating a mixture of α-, β-, or γ-emitting radionuclides) designates samples that contain either a gamma emitter or multiple emitters (alpha plus beta).

Scenario 3 takes place when the radioactive contaminants have been well characterized. Detailed analyses are required for the radionuclide(s) known to be in the samples, and at the direction of the IC. Thus, the radioanalytical process chart becomes much more streamlined, and sample priority is based upon what is needed by the Incident Commander at the time the samples are taken. Either high- or low-activity samples may take priority.

Because the radionuclides are known, the gross screening instruments should be calibrated for the radionuclides of interest. This allows rapid and more accurate assessment of the activity before the analytical separations are performed.

Many of the flow diagram shapes are color-coded to reflect the analytical flow path for various combinations of decay modes (green for alpha, gray for beta, or brown for any two emitters). The accompanying numbered notes are color-coded in the same fashion, as are the examples in Appendix IV. It is highly advisable to study the flow paths in color, as a black-and-white printing may be confusing or ambiguous.

1. The event that has taken place is now characterized, and the radionuclide(s) of concern have been identified. The flowchart is trimmed to deciding which of the three different radionuclide emissions are present. The emission mode generally determines the final radioanalytical method(s) that will be used to assess the concentration. Generally, β-only emitters will be analyzed by GPC or LSC, α-only emitters by either GPC or AS, and β- and γ-emitters by gamma spectrometry. The choice is determined by what is known about the event. If more than one type of radionuclide emitter is present, the choice is to follow the (α, or β, or γ) path.

2α. This path is selected only if all the radionuclides from the event are α emitters. The samples still should be screened to distinguish high from low-activity samples. The instrument used to perform the screening analysis should be calibrated with the radionuclide of interest.

2β. This path is selected only if all the radionuclides from the event are β emitters. The samples still should be screened to distinguish high from low-activity samples. The instrument used to perform the screening analysis should be calibrated with the radionuclide of interest. If more than one radionuclide is present, the screening instrument should be calibrated with the radionuclide that is expected to produce the lowest response. This will provide screening results that are a more conservative estimate of the activity present for that radionuclide.

2μ. This path is selected only if the radionuclides from the event emit a combination of α, or β, or γ emitters. The samples still should be screened to distinguish high from low-activity

samples. The instrument used to perform the screening analysis should be calibrated with the radionuclide of interest.

3α. 3β. 3μ. The purpose of this step is to distinguish high-activity samples from low-activity samples and to rank the samples in order of their activity level. The subsequent flow paths would be selected based on the priority from the IC. Thus, it is important that this screening method is able to distinguish high-activity samples from low-activity samples in a reasonably short time. Using a 1-hour count time as the maximum and a 10-mL aliquant as the minimum, Table 12 in Appendix VI demonstrates the capability for MDC and critical-level values that can be achieved routinely using LSC or GPC analytical methods. Although these MDCs are not equivalent and do not relate to a specific DWC, they are low enough to be used for screening purposes. The samples should be numerically ranked based on their gross concentration and processed according to the priority specified by the IC.

> NOTE: The flow of priority splits here. Either of the paths for the suffixes 1 or 2 may get the priority. The difference is that suffix 1 is for SDWA requirements, and that suffix 2 flow path would be for IC-determined MQOs. Flow path 2 would be scaled to the appropriate ADL based on the 100-mrem values.

$4\alpha_1$ $4\beta_1$ $4\mu_1$ The first analytical priority when this path is chosen is for the known contaminant(s) from the event. This should use a radionuclide-specific method, and the RDL should be less than or equal to that shown in Table 7A or 7B. This path would be chosen if the intent was to look for potable water sources. If the event-specific contaminant is less than its respective MCL in Table 7A or 7B, then analysis for all other SDWA contaminants should proceed. If the event-specific contaminant concentration is greater than its respective MCL in Table 7A or 7B, notify the IC that this is not a potential potable water source.

$4\alpha_2$ $4\beta_2$ $4\mu_2$ The first analytical priority when this path is chosen is for the known contaminant from the event. This should use a radionuclide-specific method, and the ADL concentration plus corresponding u_{MR} value should be a multiple of the value found in Table 6A or 6B (these tables are for the 100-mrem ADLs; the multiple would be based on the ratio of 100-mrem value to the maximum dose for the particular event). This path would be chosen if the direction were to identify water sources that may cause exposure in excess of the maximum dose allowed for the event. If the event-specific contaminant is less than its respective ADL (based on scaling of concentrations and in Tables 6A or 6B), then analysis for all other contaminants of concern should proceed. If the event-specific contaminant concentration is greater than its respective ADL for that event, notify the IC that this sample has exceeded the event-specific AAL.

$5\alpha_1$ $5\beta_1$ $5\mu_1$ Perform all other radionuclide SDWA required analyses.

$5\alpha_2$ $5\beta_2$ $5\mu_2$ Perform all other event related or requested radionuclide analyses.

$6\alpha_1$ $6\beta_1$ $6\mu_1$ Select the MCL values from Tables 7A or 7B to be compared with the final

analytical concentrations for the water sample.

$6\alpha_2$ $6\beta_2$ $6\mu_2$ Select the ADL values from Tables 6A or 6B (scaled to the AAL for the event) to be compared with the final analytical concentrations for the water sample.

7. Compare the final results with the screening analysis and verify that no major nuclide has been missed: the sum of the individual nuclide concentrations (excluding tritium if the screening measurement was made by GPC) is approximately equivalent to the gross activity concentration (a rule of thumb is within a range of about half to twice the gross value). This check will ensure that the sum of the measurements compares reasonably to the total measured gross activity. Activity concentrations due to decay products should be included in the verification. If there is a discrepancy between the summed activity concentration of all statistically significant individual nuclide concentrations (i.e., sum all results detected at levels greater than the RDL or for drinking water), check for errors and resolve any discrepancies prior to proceeding.

8. If the sum of the fractions of all β- and γ-emitting radionuclides present exceeds 1.0, verify analyses or calculations. The sample would have concentrations that exceed the 40 CFR limits. If the individual results and the sum of the fractions are less than their respective limits, report results to IC.

9. Several actions lead to this step:

- In steps $4\alpha_1$, $4\beta_1$, and $4\mu_1$, the result for the event-specific radionuclide exceeded the MCL for the radionuclide in potable water.
- From Step 8, all analyses indicated that the sample is within the limits of the MCLs from the SDWA.
- In steps $4\alpha_2$, $4\beta_2$, and $4\mu_2$, the event-specific radionuclide exceeded the ADL for the event.
- From Step 10 if the sum of fractions is greater than 1.0.
- From Step 10 if gross activity and sum of individual radionuclide activities in sample do not match within 0.5 to 2.0.

Notify the IC of the specific final results for all samples, with a description of any unresolvable discrepancies. All sample residuals or final counting forms should be archived until notification to dispose of them is received.

10. The results from the radionuclide-specific analysis and the gross measurement should match to within a factor of 0.5 to 2.0. If they do not, re-analysis may be required starting with the gross-activity measurement. It is possible that either a short-lived radionuclide activity has decayed away prior to having been analyzed, or a radionuclide analysis was missed. In either case, the discrepancy should be resolved, which may include specific correlations for the radionuclides from this event.

If this step is arrived at as a result of the sum of fractions being greater than 1.0, verify the data to ensure correctness and that the gross activity and sum of individual activities are within a factor of 0.5 to 2.0. When this review is completed, notify the IC of results per Step 9.

Appendix I. Tables of Radioanalytical Parameters for Radionuclides of Concern

TABLE 5A – Analytical Decision Levels (ADL) and Required Method Uncertainty For Gross Alpha Screening Analysis

Radionuclide	Half-Life [1]	Additional Emissions	pCi/L			
			500-mrem [2]		100 mrem [2]	
			ADL	Required Method Uncertainty [4, 5] (u_{MR})	ADL	Required Method Uncertainty [4, 5] (u_{MR})
Gross α Screen	—		1.0×10^3	6.1×10^2	200	120
Am-241 [3]	432.2 y	γ	1.0×10^3	6.1×10^2	200	120
Cm-242	162.8 d		7.0×10^3	4.3×10^3	1.4×10^3	8.5×10^2
Cm-243	29.1 y	γ	1.3×10^3	760	250	150
Cm-244	18.10 y		1.5×10^3	8.8×10^2	290	1.8×10^2
Np-237	2.144×10^6 y	γ	2.0×10^3	1.2×10^3	390	2.4×10^2
Po-210	138.4 d		65	40	13	7.9
Pu-238	87.7 y		900	550	180	110
Pu-239	2.411×10^4 y		850	520	170	100
Pu-240	6.564×10^3 y		850	520	170	100
Ra-226	1.600×10^3 y	γ DP	460	280	90	55
Th-228	1.912 y	γ DP	1.3×10^3	790	260	160
Th-230	7.538×10^4 y		900	550	180	110
Th-232	1.41×10^{10} y	γ DP	800	490	160	97
U-234	2.455×10^5 y	γ DP	3.2×10^3	1.9×10^3	650	400
U-235	7.038×10^8 y	γ DP	3.3×10^3	2.0×10^3	650	400
U-238	4.468×10^9 y	γ DP	3.5×10^3	2.1×10^3	700	430

Notes:

[1] The half-lives of the nuclides are given in years (y) or days (d). DP refers to "decay products." Radionuclide above the gray bar is default for calibrating screening instrumentation.

[2] The values in this table correspond to the numbered rectangles 2 and 7 in Radioanalytical Scenario 1.

[3] The u_{MR} and ADL for ^{241}Am are used for gross alpha screening.

[4] The relative required method uncertainty (φ_{MR}) for values greater than the AALs in Table 10A of Appendix VI can be obtained by dividing the u_{MR} value in this table by the corresponding AAL value in Table 10A.

[5] The individual required method uncertainty (u_{MR})values in this table apply up to the corresponding values for AALs or 100-mrem values, respectively, identified in the tables in Appendix VI. Above the values noted in the Appendix VI tables, the relative required method uncertainty (φ_{MR})would apply.

TABLE 5B – Analytical Decision Levels (ADL) For Gross Beta or Gamma Screening Analysis

Radionuclide	Emission Type	Half-Life [1]	pCi/L			
			500 mrem		100 mrem	
			ADL	Required Method Uncertainty [3, 6] (u_{MR})	ADL	Required Method Uncertainty [3, 6] (u_{MR})
Beta Gamma Screen[2]	βγ	30.07 y	2.9×10^4	1.8×10^4	6.0×10^3	3.6×10^3
Sr-90[2]	β (β DP)	28.79 y	6.0×10^3	3.6×10^3	1.2×10^3	730
Co-60[2]	βγ	5.270 y	1.7×10^4	1.0×10^4	3.3×10^3	2.0×10^3
Ac-227+DP	β (α DP)	21.77 y	550	330	110	67
Ce-141	βγ	32.51 d	1.1×10^5	6.7×10^4	2.2×10^4	1.3×10^4
Ce-144	βγ	284.9 d	1.5×10^4	8.8×10^3	2.9×10^3	1.8×10^3
Co-57	γ	271.1 d	3.2×10^5	1.9×10^5	6.5×10^4	4.0×10^4
Cs-134	βγ	2.065 y	2.2×10^4	1.3×10^4	4.3×10^3	2.6×10^3
Cs-137	βγ	30.07 y	2.9×10^4	1.8×10^4	6.0×10^3	3.6×10^3
H-3	weak β	12.32 y	3.9×10^6	2.3×10^6	7.5×10^5	4.6×10^5
I-125	γ	59.40 d	6.5×10^3	4.0×10^3	1.3×10^3	790
I-129	βγ	1.57×10^7 y	1.7×10^3	1.0×10^3	330	200
I-131	βγ	8.021 d	2.7×10^3	1.6×10^3	550	330
Ir-192	βγ	73.83 d	6.0×10^4	3.6×10^4	1.2×10^4	7.3×10^3
Mo-99	β γ (γ DP)	65.94 h	1.6×10^5	9.7×10^4	3.2×10^4	1.9×10^4
P-32	β	14.26 d	3.0×10^4	1.8×10^4	6.0×10^3	3.6×10^3
Pd-103	γ	16.99 d	3.9×10^5	2.4×10^5	8.0×10^4	4.9×10^4
Pu-241	β	14.29 y	5.0×10^4	3.0×10^4	1.0×10^4	6.1×10^3
Ra-228	β (γ DP)	5.75 y	80	49	16	9.7
Ru-103	βγ	39.26 d	1.2×10^5	7.0×10^4	2.3×10^4	1.4×10^4
Ru-106	βγ	373.6 d	1.1×10^4	6.7×10^3	2.2×10^3	1.3×10^3
Se-75	γ	119.8 d	3.4×10^4	2.0×10^4	6.5×10^3	4.0×10^3
Sr-89	β	50.53 d	3.2×10^4	1.9×10^4	6.5×10^3	4.0×10^3
Tc-99	βγ	2.11×10^5 y	1.2×10^5	7.3×10^4	2.4×10^4	1.5×10^4

Notes:

[1] The half-lives of the nuclides are given in years (y), days (d), or hours (h). DP refers to "decay products." Radionuclides above the gray bar are the default radionuclides for calibrating screening instrumentation.

[2] The AAL and associated u_{MR} and ADL values for ^{137}Cs are used for initial beta gamma screening analysis on sample bottle (Step 1 in Radioanalytical Scenarios 1 and 2). The AAL and associated u_{MR} and ADL values for ^{60}Co concentration are used for gross gamma measurements thereafter (see text). The AAL and associated u_{MR} and ADL values for ^{90}Sr are the defaults used gross beta screening.

[3] The relative required method uncertainty (φ_{MR}) for values greater than the AAL values in Table 10B of Appendix VI can be obtained by dividing the u_{MR} value in this table by the corresponding AAL value in Table 10B.

[4] Several nuclides in Table 5B decay by electron capture. These radionuclides cannot be detected using gross β analysis. The electron-capture decay leads to characteristic X-rays of the progeny nuclide. The most effective way to detect the X-rays from these electron-capture-decay radionuclides is either with a low-energy photon detector (LEPD) or a reverse electrode germanium detector (N-type semiconductor detector). The lower energy range of these detectors is about 10 keV.

[5] If γ isotopic analysis versus gross γ analysis is used for rectangles 2 and 7 in Radioanalytical Scenario 1, comparisons should be made to the value specific for the radionuclide found in the γ analysis listed in this table.

[6] The individual required method uncertainty (u_{MR}) values in this table apply up to the corresponding values for AALs or 100-mrem AALs identified in the tables in Appendix VI. Above the values noted in the Appendix VI tables, the relative required method uncertainty (φ_{MR}) applies.

TABLE 6A – Required Method Uncertainties for Alpha-Emitting Radionuclides at 100-mrem AAL When Using Radionuclide-Specific Methods

	pCi/L	
Radionuclide	**100-mrem ADL [1]**	**Required Method Uncertainty at or Below 100-mrem AAL [2, 3, 4]** u_{MR}
Am-241	280	50
Cm-242	2.0×10^3	350
Cm-243	350	63
Cm-244	410	73
Np-237	550	98
Po-210	18	3.3
Pu-238	250	45
Pu-239	240	43
Pu-240	240	43
Ra-226	130	23
Th-228	370	65
Th-230	250	45
Th-232	230	40
U-234	920	160
U-235	920	160
U-238	990	180

Notes:

[1] Only the 100-mrem ADL and the associated required method uncertainty (u_{MR}) are shown.

[2] See Appendix VI for the rationale and methodology used in determining these values.

[3] These method uncertainties are applicable to each radionuclide when a radionuclide-specific method is used to determine the activity result .

[4] The values corresponding to an AAL of 100 mrem were chosen for these tables. These values can be used to conveniently scale to other project-specific AALs. For example, if a specific project had AALs at 20 mrem (one-fifth of 100 mrem), the table values can be scaled down simply by dividing the listed values by five. Thus, for an analytical action level of 20 mrem, the respective values for ^{210}Po would be one fifth the values listed in Table 10A and this table:

$$\text{20-mrem AAL} = [\text{100-mrem AAL} / 5] = [26/5] \approx 5.2 \text{ pCi/L},$$

$$\text{20-mrem } u_{MR} = [\text{100-mrem } u_{MR} / 5] = [3.3/5] \approx 0.66 \text{ pCi/L}$$

and the corresponding 20-mrem ADL would be:

$$\text{20-mrem ADL} = [\text{100-mrem ADL}/5] = [18/5] = 3.6$$

See Appendix VI for details of these calculations.

TABLE 6B – Required Method Uncertainties for Beta- or Gamma-Emitting Radionuclides at 100-mrem AAL When Using Radionuclide-Specific Methods

Radionuclide	pCi/L	
	100-mrem ADL [1]	Required Method Uncertainty at or Below 100-mrem AAL [2, 3, 4] u_{MR}
Ac-227+DP	160	28
Ce-141	3.1×10^4	5.5×10^3
Ce-144	4.1×10^3	730
Co-57	9.2×10^4	1.6×10^4
Co-60	4.7×10^3	830
Cs-134	6.1×10^3	1.1×10^3
Cs-137	8.5×10^3	1.5×10^3
H-3	1.1×10^6	1.9×10^5
I-125	1.8×10^3	330
I-129	470	83
I-131	780	140
Ir-192	1.7×10^4	3.0×10^3
Mo-99	4.5×10^4	8.1×10^3
P-32	8.5×10^3	1.5×10^3
Pd-103	1.1×10^5	2.0×10^4
Pu-241	1.4×10^4	2.5×10^3
Ra-228	23	4.0
Ru-103	3.3×10^4	5.8×10^3
Ru-106	3.1×10^3	550
Se-75	9.2×10^3	1.6×10^3
Sr-89	9.2×10^3	1.6×10^3
Sr-90	1.7×10^3	300
Tc-99	3.4×10^4	6.0×10^3

Notes:

[1] Only the ADL of 100 mrem and the associated required method uncertainty (u_{MR}) are shown.

[2] See Appendix VI for the rationale and methodology used in determining these values.

[3] These method uncertainties are applicable to each radionuclide when a radionuclide specific method is used to determine the activity result.

[4] The values corresponding to an AAL of 100 mrem were chosen for these tables and can be used to conveniently scale to other project-specific AALs. For example, if a specific project had AALs at 20 mrem (one-fifth of 100 mrem), the table values can be scaled down simply by dividing the listed values by five. Thus, for an AAL of 20 mrem, the value for ^{90}Sr would be one-fifth the values listed in Table 10B and this table:

$$20 \text{ mrem AAL} = 100 \text{ mrem AAL} / 5 = [2400/5] = 480 \text{ pCi/L}$$

$$20 \text{ mrem } u_{MR} = 100 \text{ mrem } u_{MR} / 5 = [300/5] = 60 \text{ pCi/L}$$

and its corresponding ADL would be:

$$20 \text{ mrem ADL} = 100 \text{ mrem ADL} / 5 = [1700 / 5] = 340 \text{ pCi/L}$$

See Appendix VI for details of these calculations.

TABLE 7A – Maximum Contaminant Levels (MCL) and Required Detection Levels (RDL) for Alpha-Emitting Radionuclides in Water

Radionuclide	Drinking Water MCL [1] pCi/L (mg/L) [2]	Drinking Water RDL[5] pCi/L (mg/L) [2]
Gross α Screen	15	3[4]
Am-241	15 (4.4×10^{-9})	1.5 (4.4×10^{-10})
Cm-242	15 (4.5×10^{-12})	1.5 (4.5×10^{-13})
Cm-243	15 (3.0×10^{-10})	1.5 (3.0×10^{-11})
Cm-244	15 (1.8×10^{-10})	1.5 (1.8×10^{-11})
Np-237	15 (2.2×10^{-5})	1.5 (2.2×10^{-6})
Po-210	15 (3.3×10^{-12})	1.5 (3.3×10^{-13})
Pu-238	15 (8.9×10^{-10})	1.5 (8.9×10^{-11})
Pu-239	15 (2.4×10^{-7})	1.5 (2.4×10^{-8})
Pu-240	15 (6.6×10^{-8})	1.5 (6.6×10^{-9})
Ra-226 [3]	5 (5.1×10^{-10})	1.0 (1.3×10^{-10})
Th-228 [3]	15 (1.8×10^{-11}	1.5 (1.8×10^{-12})
Th-230	15 (7.3×10^{-7})	1.5 (7.3×10^{-8})
Th-232	15 (1.4×10^{-1})	1.5 (1.4×10^{-2})
U-234	—	—
U-235	—	—
U-238	20 (3.0×10^{-2})	2.0 (3.0×10^{-3})
U-Nat	20 (3.0×10–2)	2.0 (3.0×10–3)

Notes:
[1] Continuous intake.
[2] Value in parenthesis is mass concentration units, (ppm).
[3] Combined concentration of ^{228}Ra and ^{226}Ra not to exceed 5 pCi/L.
[4] Value for RDL taken from 40 CFR 141.26(a)(2)(iii). See "Final Implementation Guidance for Radionuclides," EPA 816-F-00-002, March 2002. Available at: www.epa.gov/safewater/radionuclides/compliancehelp.html.
[5] RDL value taken as 1/10 of the MCL value if not otherwise specified in the regulations.

TABLE 7B – Maximum Contaminant Levels (MCL) and Required Detection Levels (RDL) for Beta/Gamma-Ray Emitting Radionuclides in Drinking Water

Radionuclide	Drinking Water MCL [1] pCi/L (mg/L) [2]	Drinking Water RDL [6] pCi/L (mg/L) [2]
Gross β Screen	50	5.0
Ac-227+DP [4]	15	1.5
Ce-141	300 (1.1×10^{-11})	30 (1.1×10^{-12})
Ce-144	29, 30[4] (9.4×10^{-12})	2.9, 3.0 (9.4×10^{-13})
Co-57	1,000 (1.2×10^{-10})	100 (1.2×10^{-11})
Co-60	100 (8.8×10^{-11})	10 (8.8×10^{-12})
Cs-134	80 (6.2×10^{-11})	10 (7.8×10^{-12})
Cs-137	200 (2.3×10^{-9})	20 (2.3×10^{-10})
H-3	2.0×10^{4} (N/A)	1,000 (N/A) [7]
I-125	30 (1.7×10^{-12})	3.0 (1.7×10^{-13})
I-129	1 (5.7×10^{-6})	0.1 (5.7×10^{-7})
I-131	3 (2.4×10^{-14})	1.0 (8.0×10^{-15}) [7]
Ir-192	100 (1.1×10^{-11})	10 (1.1×10^{-12})
Mo-99	600 (1.2×10^{-12})[5]	60 (1.2×10^{-13})
P-32	30 (1.0×10^{-13})[5]	3.0 (1.0×10^{-14})
Pd-103	900 (1.2×10^{-11})[5]	90 (1.2×10^{-12})
Pu-241	300 (2.9×10^{-9})[5]	30 (2.9×10^{-10})
Ra-228 [3]	5 (1.8×10^{-11})	1.0 (3.7×10^{-12})[7]
Ru-103	200 (6.2×10^{-12})	20 (6.2×10^{-13})
Ru-106	30 (9.1×10^{-12})	3.0 (9.1×10^{-13})
Se-75	900 (6.2×10^{-11})	90 (6.2×10^{-12})
Sr-89	20 (6.9×10^{-13})	10 (3.4×10^{-13}) [7]
Sr-90	8 (5.8×10^{-11})	2.0 (1.4×10^{-11}) [7]
Tc-99	900 (5.3×10^{-5})	90 (5.3×10^{-6})

Notes:

[1] Continuous intake.

[2] Value in parenthesis is mass concentration units (ppm).

[3] Combined concentration of ^{228}Ra and ^{226}Ra not to exceed 5 pCi/L.

[4] Includes decay products originating from the ^{227}Ac in the body. Used only to calculate the concentration (pCi/L) or dose from ^{227}Ac in the body. DP refers to "decay products."

[5] Value from OSWER Directive 9283.1-14, Appendix B: "Use of Uranium Drinking Water Standards under 40 CFR 141 and 40 CFR 192 as Remediation Goals for Groundwater at CERCLA sites." November 6, 2001. Available at: www.epa.gov/superfund/health/contaminants/radiation/pdfs/9283_1_14.pdf..

[6] RDL value taken as 1/10 of the MCL value if not otherwise specified in the regulations.

[7] RDL value taken from "Radionuclides Notice of Data Availability Technical Support Document,"(March 2000). Available at: www.epa.gov/safewater/rads/tsd.pdf. 40 CFR 141.26(a)(2)(iii). See "Final Implementation Guidance for Radionuclides," EPA 816-F-00-002, March 2002. Available at: www.epa.gov/safewater/radionuclides/compliancehelp.html.

APPENDIX II. Example of High Radionuclide Concentration in Water (Radioanalytical Scenario 1)

Description

Surface water, storm water, drinking water, and estuaries have been impacted by an RDD. The specific radionuclides causing the radiological incident have not yet been determined, nor has their concentration in these samples. The event sequence in the laboratory assumes a single analyst following the analytical process chart, under conditions of single process stream. Analysis at this point is to assess if the 500-mrem AAL[1] values are exceeded by measurement of the sample's total gross radioactivity with hand-held survey instruments. These might include a survey meter or Geiger-Muller counter with appropriately calibrated beta and gamma detector probes or a micro-roentgen meter (gamma only).[2] This step would most likely be performed with the sample container, unopened, leaving the determination of α AAL values to the next step. Unless the identification of the radionuclide contamination is known, the hand-held survey instrument should be calibrated to respond to a gross screening β and γ concentration of 5.8×10^4 pCi/L; a ^{137}Cs calibration source should be used. If the identity of the radionuclide(s) is known, the ADL for the radionuclide listed for the 500-mrem value is to be used (see Table 5B, page 33). For survey instruments having an exposure rate readout, the instruments should be calibrated in terms of pCi/L per exposure unit readout for each container geometry expected and for the nuclide of interest (^{137}Cs for unidentified nuclides).

Event Sequence

It is Day 1 of the event. The incident responders have established a field office for coordinating response efforts, including a laboratory project manager. At 1200 hours of Day 1, the incident-response team sends a laboratory three water samples taken from the affected area that they believed to be significantly above background radiation levels. The samples arrive at the laboratory at *Day 1, 1500 hours.*

Analysis Path

Laboratory personnel perform an initial scan of the three 1-liter sample containers using a hand-held survey meter with appropriate detector probe obtaining the data in the table below. The average beta detection efficiency is 30%, and one may assume that the probe responds only to 10% of the decays from the sample bottle. Thus, the overall beta-detection efficiency for this scanning technique is 3 %. The overall gamma survey instrument response (a NaI(Tl) detector) conversion factor for this sample geometry (i.e., the one-liter sample bottle) is 53.6 pCi/(μR/h).

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[1] Depending on the time of the response, a 2-rem PAG may be applicable. If so, the radionuclide concentrations corresponding to the 2-rem PAG DWC can be calculated by taking the values for the 100-mrem column in the table and multiplying by 20.

[2] Some manufacturers have developed kits that include the survey meter plus an alpha–beta–gamma pancake GM detector and a NaI gamma detector.

Container ID	Gross Beta, cpm	Gross Gamma, µR/h
1	5,100	1,175
2	470	57
3	300	35
Background	300	35

Alpha analysis has not yet been performed on these samples. The sample measurements from the above table are converted to units comparable to those in Table 6A for Container 1 having a 1-L volume as follows:

$$\text{Gross Beta Activity} = \frac{(5100 - 300)\ \text{cpm}}{(3.7 \times 10^{-2}\ \text{dps / pCi}) \times 60\ \text{s / min} \times 0.03} = 72{,}070\ \text{pCi / L}$$

and

$$\text{Gross Gamma Activity} = (1{,}175\text{-}35\ \mu\text{R/h}) \times (53.6\ \text{pCi / } \mu\text{R/h}) = 61{,}104\ \text{pCi/L}.$$

The gross beta result exceeds the screening ADL of 2.9×10^4 pCi/L, and the gamma value exceeds the gross screening gamma ADL for ^{137}Cs in Table 5B (4.1×10^4 pCi/L), which take the sample priority to the **red** flow path for Container 1, Step 2, of Figure 2 (page 13).

A similar analysis for Container 2 yields 2,552 pCi/L beta and 1,179 pCi/L gamma. This takes us to the **green** flow path for Container 2 because it is less than the gross screening value of 2.9×10^4 pCi/L. Container 3 is measuring the equivalent of background dose rates, and at this point would be relegated to the **yellow** flow path. *The time is Day 1, 1600 hrs*.

Step 2, Container 1. A 5-mL aliquant of Container 1 is taken for gross alpha/beta analysis by liquid scintillation counting and gross gamma by Na(I)Tl. The net 15-min count rate for beta is 9.25×10^2 cpm (corrected for full open window efficiency of 0.60, yields 1.38×10^5 pCi/L), and for alpha is 1.14×10^2 cpm (corrected for full open window efficiency of 0.10, yields 1.02×10^5). The laboratory compares the pCi/L values with those in Tables 5A and 5B. The laboratory personnel will find that both alpha and beta values exceed the maximum ADL concentration listed (^{241}Am for alpha and ^{90}Sr for beta).

The laboratory notes that the liquid scintillation gross beta counts far exceed the survey instrument gross beta counts. This indicates the presence of low energy beta emitters that would not be detected by a survey instrument.

The gross gamma count of 2.65×10^2 cpm (corrected for 85% efficiency to 2.8×10^4 pCi/L) is also greater than the ADL concentration in Table 5B (1.6×10^4 for ^{60}Co). The well NaI(Tl) detector display indicates the presence of several gamma ray peaks in the spectrum. The sample stays on the fast track **(red)** for analysis.

The time is Day 1, 1700 hours.

Step 3, Container 1. The laboratory compares the results of the Step 2 screening analyses with the 500-mrem ADL concentrations for screening in Tables 5A and 5B and determines that ADL concentrations have been exceeded for Container 1 for all three classes of analytes (α, β, and γ).

The laboratory manager promptly notifies the IC that initial screening indicates that the 500-mrem AAL concentrations may have been exceeded for Container 1.

A sub-sample (aliquant) would be taken for each class of analysis (three total). While the digestions of the sub-samples for alpha (Step 4) and beta (Step 5) specific analyses are being performed, the third sample will be counted on an HPGe detector for about 1 hour (Step 6) for specific gamma ray identification.

The gamma spectrum will show net activity in several gamma peaks: 186, 295, 352, 609, 1,120, and 1,764 keV. These gamma peaks will be significantly above detector backgrounds for these energies, which correspond to ^{226}Ra (and ^{214}Pb/^{214}Bi progeny of ^{222}Rn and ^{226}Ra). This suggests to the analyst at least that ^{226}Ra is present. Activity estimates for ^{226}Ra can be made from the gamma-spectrometry data for the 186-keV peak. Due to the diffusion of ^{222}Rn from water, it is expected that equilibrium between ^{226}Ra and ^{222}Rn (and decay progeny) in the water sample will not be attained. As such, the ^{226}Ra activity estimates from the ^{226}Ra/^{222}Rn progeny photopeaks 295, 352, 609, 1,120, and 1,764 keV will be biased low. However, it will show that the total beta activity does not come from only the contribution of the radium progeny. *The time is Day 1, 1830 hours.*

NOTE: No peak at 661 keV for ^{137}Cs is found. The survey instruments used for screening analysis should be recalibrated with a gamma emitter that more closely matches the gamma energies of the ^{214}Pb/Bi radionuclides.

It must be kept in mind that the gamma spectrum has eliminated the possibility of ^{131}I and ^{137}Cs, for this sample. However, tritium must be analyzed specifically, as its presence cannot be detected with the initial survey instruments and may be obscured during the gross liquid scintillation analysis due to the presence of the other beta emitters in high concentrations (see caution about beta mismatch in the preceding note about Step 2). Thus, an aliquant of the original sample or that used for the gamma spectrometry should be distilled, and the distillate analyzed for tritium. Sample analysis for tritium indicates 80,000 pCi/L tritium present at *Day 1, 1930 hours.*

When the alpha- and beta-specific analyses are completed, only ^{90}Sr at 8,000 pCi/L, ^{226}Ra at 28,000 pCi/L (and their respective progeny) and ^{3}H at 80,000 pCi/L are found. It is important to note that the total gamma activity from ^{226}Ra and its decay products is only about 80% of the total beta activity from these radionuclides. This is due to the low abundance of the gamma rays from this group of radionuclides.

Step 15, Container 1. These values are reviewed and are within about 25% of predicted from the gross analysis performed in Step 2. The value for ^{226}Ra exceeds the 500-mrem ADL concentration of 460 pCi/L, ^{90}Sr value exceeds the 500-mrem ADL concentration of 6.0×10^{3}, and ^{3}H exceeds the 20,000 pCi/L MCL from the SDWA. These results are transmitted to the Incident Command Post. *The time is Day 1, 2030 hours.*

The remainder of the original sample is preserved, potentially for future analysis. The analysis of the container with the next highest priority based on dose would now proceed.

Step 7, Container 2. This container has initial measurements of 470 cpm beta and 57 µR/h gamma

corresponding to 2,552 pCi/L[1] gross beta and 1,179 pCi/L gross gamma. It will follow the green flow path from Step 1. The analysis of a 5-mL aliquant for a 15-minute gross alpha/beta count by liquid scintillation will proceed.

Steps 8 and 9, Container 2. Step 7 yields a gross alpha value of 2.8×10^{-1} cpm (corrected for full open window efficiency of 0.10, yields 2.52×10^{2} pCi/L) and gross beta value of 17 cpm (corrected for full open window efficiency of 0.60 , yields 2.55×10^{3} pCi/L). These, when compared to the values in Tables 5A and 5B, verify that the 500-mrem ADL concentrations have not been exceeded, but the 100-mrem ADL screening values of 2.0×10^{2} pCi/L (based on ^{241}Am) and 1.2×10^{3} (based on ^{90}Sr) have been exceeded. *The time is Day 1, 2100 hours.*

Step 10, Container 2. Analysis of alpha, beta, and gamma-specific radionuclides begins. Gamma spectrometry indicates no gamma rays are present except for those from ^{226}Ra progeny. *The time is Day 1, 2230 hours.*

The aliquant from Container 2 is analyzed for tritium directly and found to contain 1800 pCi/L. *The time is Day 1, 2330 hours.*

First results from the alpha- and beta-specific analyses are completed. *The time is Day 2, 0300 hours.*

All alpha- and beta-specific analyses are completed. Supervisory review of results is completed, identifying the presence of ^{226}Ra (6.3×10^{1} pCi/L) and ^{90}Sr (3.0×10^{2} pCi/L). *The time is Day 2, 1300 hours.*

Steps 15 and 16, Container 2. Comparison of the gross alpha and gross beta to the sum of the alpha- and beta-emitting radionuclides matches to within 30%. None of the individual values of the identified radionuclides exceed their respective 100-mrem ADL concentration. Nor does the sum of the fractions of the β- and γ-emitting radionuclides (0.126) exceed the aggregate AAL (1.0).[2] Thus neither exceeds the 100-mrem level. Results are reported to the Incident Commander. The remainder of the original sample is preserved for future analysis. The analysis of the container with the next highest priority (based on dose) would now proceed. *The time is Day 2, 1500 hrs.*

Step 11, Container 3. Initial micro-R or survey meter screening of this sample resulted in a dose rate equivalent to background, and the sample aliquants analyzed by LSC also were equivalent to

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[1](470-300)/[(0.03)(2.22) = 2,552 pCi/L beta, (57-35)[53.6 pCi/ (μR/h)] = 1,179 pCi/L gamma

[2]The sum of the fractions is calculated as follows using the values from Tables 10A and 10B (Appendix VI) under the 100-mrem level (green) columns (Note that the contribution from α emitters is not included as part of the sum of fractions.):

Radionuclide	Table 10A or 10B Value (pCi/L)	Sample Concentration From Radioanalytical Scenario (pCi/L)	Fraction
^{3}H	1.5×10^{6}	1.8×10^{3}	1.2×10^{-3}
^{90}Sr	2.4×10^{3}	3.0×10^{2}	1.25×10^{-1}
Sum	—	—	0.126

background in the short count. Following Step 9 on the decision tree, the gross beta-to-gamma ratio (Step 11) is calculated for a 10–15-mL aliquant of the sample (dried onto a planchet) and counted with a hand-held device. (It also would be possible to use the gross count data from the LSC and gamma spectrometry analyses to compute this value if more convenient for the analyst.) If the ratio is greater than 2.5, there is a strong possibility that ^{90}Sr is present and that analysis should be immediately initiated. Due to the low activity in this sample, it is unlikely that it has been affected by the event, but it is prudent to determine whether if abnormal levels of ^{90}Sr are present. Due to the low activity in this sample, it is unlikely that it has been affected by the event. It is preserved, and, if necessary, analysis may be resumed later at Step 12. *The time is Day 2, 1600 hours.*

Steps 12 and 13, Container 3. A 250-mL aliquant of the sample is counted by GPC to assess the gross alpha and beta values with respect to the maximum contaminant level (MCL). If gross alpha or gross beta is greater than 5 or 50 pCi/L, respectively, then the radionuclide-specific analyses should be performed if deemed necessary by the IC. If both are less than these values, the remainder of the original sample should be archived for analysis at a later time (Step 17). If this sample is less than both 5 and 50 pCi/L for alpha and beta, respectively, then it may be suitable as a drinking water source, and further analysis would be required. The actual gross alpha and beta results are 2 and 5 pCi/L, respectively. *The time is Day 2, 1800 hours.*

Steps 14 and 15, Container 3. The sample analyses have been completed for all alpha, beta and gamma emitters. Only traces of strontium above background (0.5 pCi/L) have been detected. The results are reviewed and transmitted to the IC. *The time is Day 2, 2100 hours.*

Elapsed time from receipt of samples at laboratory: 30 hours.

APPENDIX III. Example of Finding a Potable Water Source (Radioanalytical Scenario 2)

Description[1]

During the intermediate phase following the detonation of an RDD, sources of potable water will need to be evaluated for radioactive contamination. For this scenario, the priority switches from the high priority for high-activity samples (clearly not potable) to high priority for low-activity samples. Thus, all water samples are screened for gross alpha and beta radioactivity based on the MCL screening levels, and those samples having gross radioactivity concentrations *below* the MCL have priority for specific contaminant analyses. The radionuclide contaminants that initiated the incident should have been completely characterized by now under "Radioanalytical Scenario 1," and their results would lead into the specific radioanalytical processes. However, it is possible that the water sources may have other radionuclide contaminants, either related to the initial incident or from naturally occurring sources, which also will need to be characterized. It is important to note that the priority flow path for this scenario is set up the *opposite* of Radioanalytical Scenario 1: the high priority flow path is for those samples that have very low activity. Additionally the flow diagrams are based on the concept of establishing the MDC as the AAL. Thus, the values for the ADLs are calculated using Tables 11A and 12 in Appendix VI.

Event Sequence

It is Day 8 following an RDD event. The intermediate phase of the event is ongoing. The Incident Command Center has dispatched three samples to be assessed for their potential as drinking water sources for population areas where people will be returning to live.

The time frame for results is not as critical as in Radioanalytical Scenario 1, but prompt identification of drinking water sources is important in rebuilding public confidence in the cleanup effort. The only radionuclides that have been identified in any of the samples to date are ^{226}Ra (and its progeny), ^{3}H, and ^{90}Sr. The beta survey meter has been calibrated with a ^{90}Sr-specific source, and an overall efficiency for a 1 liter sample geometry is found to be 8%. The response of the micro-R meter to a radium source has been found to be 70 pCi/(μR/h).

The three samples arrive at the laboratory at 0800 on Day 8.

Analysis Path

The three samples are screened upon arrival using a micro-R meter and a beta survey meter, yielding the following results based on the instrument specific calibrations:

Sample Container	Container 5	Gross pCi/L	Container 6	Gross pCi/L	Container 7	Gross pCi/L	Instrument Background
Gross Beta, cpm	2,300	11,261	300	0	300	0	300
μR/h	38	210	36	70	35	0	35

[1]The events and radionuclides for Radioanalytical Scenario 2 are unrelated to Radioanalytical Scenario 1.

Container 5 is greater than the 100-mrem ADL concentration for ^{90}Sr (see Table 6B) and is set aside for analysis at a later date. Containers 6 and 7 are less than any 100 mrem values except for ^{228}Ra.

Steps 2a and 2b, Containers 6 and 7. The potential radionuclides are ^{226}Ra, ^{3}H, and ^{90}Sr. An 8-mL aliquant of each sample is counted for 100 minutes on a gas proportional counter (GPC) with the following results. (See Appendix VI, Table 12, for approximate counting times. Laboratory personnel should use specific correction factors from their instruments to determine these times).

Sample Container	Container 6	Container 7	Reagent Blank Background
GPC cpm, alpha	0.04	0.02	0.02
GPC cpm, beta	145	12.3	4.5

Container 6 gross beta result is greater than 10,000 pCi/L, and the high GPC result compared to the beta screening result indicates a low energy beta emitter. Therefore, it is checked for preservation requirements and stored for analysis in the near future (next day or two), continuing at Step 13.

Container 7 has a gross beta concentration of 84 pCi/L. This is possibly a potable water source depending upon the specific radionuclides contained in the sample. An aliquant is removed for tritium analysis (Step 4a), and will also be assessed using Steps 3, 4b, and 6. *It is Day 9, 0900 hours.*

Step 4b, Container 7. This analysis from Step 4a should be started prior to taking any other steps. An assessment of whether or not the ADL for tritium has been exceeded can be determined using LSC in about 40 minutes. For this sample, the tritium concentration is determined to be 580 pCi/L (the ADL for the analysis was determined to be 410 pCi/L). This confirms that Steps 3, 5, and 6 should proceed. *It is Day 9, 1400 hours.*

Steps 3, 5, and 6, Container 7. Due to the low reading on the micro-R or survey meter in Step 1, a larger sample size was taken for the sample in Step 2b. In order to approximate the RDL values in the SDWA, the lab selects a sample size commensurate with its normal water quality programs. Looking ahead to Step 6, the sample follows the path "5–15 pCi/L" to the next step, "Begin radionuclide-specific alpha analysis" (Step 8). Also, Step 5 divides at the 50 pCi/L level, significantly above this sample, so the next step is "begin radionuclide-specific beta analyses" (Step 7). Beta-specific and gamma analyses should be performed in parallel.

The alpha- and beta-specific analyses are completed, yielding values for ^{226}Ra of 3.6 pCi/L and for ^{90}Sr of 1.2 pCi/L. *It is Day 10, 1200 hours.*

Step 9, Container 7. While beta- and alpha-specific analyses are being performed, gamma spectrometry also should be performed on this sample. Dependent on detector efficiency and sample size used, the count time will be between about 1 to 4 hours. No gamma-ray emitters are identified in this sample, except for $^{214}Pb/^{214}Bi$. Ra-228 analysis also is performed, and results are 1.1 pCi/L. *It is Day 8, 1800 hours.*

Steps 10 and 11, Container 7. The results from Steps 4b, 7, 8, and 9 are checked against the MCL and for Container 7. All are below the MCLs. The sum of the fractions of the MCLs for all beta-gamma radionuclides determined (^{3}H and ^{90}Sr) is 0.179. The value for $^{226}Ra + ^{228}Ra$ is 4.7 and is less than the MCL for drinking water. Because these values are less than their respective limits, the water

may be acceptable as a potable water source. However, the laboratory should continue with all remaining samples because a single radiologically potable water supply may not be adequate. The analysis results are sent to the Incident Command Center. *It is Day 8, 2300 hours.*

Step 13, Container 6. Although this sample had a low overall micro-R or survey meter reading, it was preserved because of its statistically significant count rate above the reagent blank reading. The process, based on a time priority, would now pick up with this sample at Steps 4a and 4b.

Step 4a, Container 6. Tritium analysis is started on this sample while preparations are begun for specific alpha, beta, and gamma spectrometry analysis. Tritium in the sample is measured at 7,780 pCi/L. *The time is Day 8, 2400 hours*.

Step 3, Container 6. The gross beta value is ~20 pCi/L (Step 5, the majority of the original LSC response in Step 2 coming from tritium), and the gross alpha value is ~9 pCi/L (Step 8).

Step 5, Container 6. The gross beta concentration is less than 50 pCi/L, so beta-specific and gamma analyses should be performed (Steps 7 and 9). Gamma spectrometry indicates no other gamma emitters except for $^{214}Pb/^{214}Bi$. Beta analyses indicate the presence of ^{90}Sr at 6.0 pCi/L. *The time is Day 9, 0400 hours.*

Steps 6 and 12, Container 6. The gross alpha indicates that it is not necessary to determine if uranium is present (Steps 12a and b). However, due to the nature of the event, uranium analysis by inductively coupled plasma-mass spectrometry is performed and subsequently shows that total uranium to be 2.7 pCi/L. The IC has requested that additional alpha specific analyses should be performed just to ensure that no other radionuclides are present (Step 8). *It is Day 9, 0200 hours.*

Step 8, Container 6. Alpha-specific analysis is performed for ^{226}Ra and indicates <1.5 pCi/L.

Steps 10 and 11, Container 6. None of the MCLs for the identified radionuclides, or the gross alpha or beta MCLs, has been exceeded. However, the sum of fractions is 1.139 form tritium and strontium. Results reported to the Incident Command Center. *The time is Day 9, 1000 hours.*

Steps 14a and b, Container 5. A 10-mL aliquant is taken from Container 5 for gross alpha and beta analysis by GPC. After counting, the values are gross alpha 3.88 pCi/L and gross beta 4.6×10^4 pCi/L. The high LSC beta value compared to the screening analysis indicates a low energy beta emitter is present. *It is Day 9, 1800 hours.*

Steps 4a and c, Container 5. LSC is performed on the sample for tritium and found to contain 35,000 pCi/L. As this is above the MCL for tritium, this sample is not suitable for drinking water. The result is reported to the IC. Other radiochemical analyses would be performed as necessary based on the requests from the IC.

The time is Day 9, 1900 hours.

Elapsed time from receipt of samples at laboratory: 35 hours.

APPENDIX IV. Radionuclide Contaminants are Known (Radioanalytical Scenario 3)

Description[1]

A public drinking water supply has been contaminated with a ^{90}Sr source. Major portions of the supply system have been isolated to prevent the spread of contamination into these portions of the system. Unlike the two earlier scenarios, the radionuclide is known. For this reason, the screening methods can be used with greater precision. For this scenario, the IC has decided that the analytical priority becomes low-activity samples because of a short-term need for reliable potable water sources. Water samples are screened only for gross beta activity based on the MCL screening levels for ^{90}Sr. The laboratory has adjusted calibration[2] of its screening survey equipment with ^{90}Sr, making the gross measurements more accurate. The efficiency with the open-end counter for ^{90}Sr is 18% for the sample geometry of a 1-L bottle. For this particular laboratory instrument, the ^{90}Sr MCL of 8.0 pCi/L would yield a net (^{90}Sr plus ^{90}Y) beta screen value of (3.2 ± 0.4) cpm. (The uncertainty is for illustrative purposes only.) Those samples having net beta activity *below* 3.2 cpm would be suspected of being below the MCL for ^{90}Sr concentration. The liquid scintillation instrument used by this laboratory has an overall efficiency for ^{90}Sr in aqueous samples of 86%, and a blank background of (2.40 ± 0.06) cpm.

The laboratory also has calibrated its gamma survey meter with a ^{137}Cs source yielding 0.017 pCi/cpm for the 1-L bottle. The radionuclide contaminants that initiated the incident should have been completely characterized using the "Radioanalytical Scenario 1" process. The water supplies sampled are likely to have radionuclide concentrations over the entire range previously seen from this event. Although the primary focus is on potable water supplies, it is of secondary importance to know where the activity is distributed in the water system. Thus, lower-priority samples (i.e., high activity) will need to be reported to the IC early on and will need to be analyzed eventually.

Event Sequence

It is *Day 3* following the dispersal of a large amount of ^{90}Sr into a drinking water supply. The source of the water in the pipeline is from a reservoir that has been analyzed and found to be uncontaminated. The intermediate phase of the event is ongoing. The Incident Command Center has dispatched three samples from different segments of the water distribution system to determine if these segments have already been contaminated.

The timing for results is as critical as in Radioanalytical Scenario 1 because the public water supply has been shut down temporarily. Rebuilding public confidence in the cleanup effort will be enhanced tremendously if portions of the system can be released for use. *The three samples arrive at the laboratory at 0800 hours on Day 3.* It is assumed that ^{90}Y is in full equilibrium with the ^{90}Sr when the samples arrive at the laboratory.

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[1]Radionuclide Scenario 3 is unrelated to either Scenarios 1 or 2.

[2]The instrumentation was calibrated previously with a ^{137}Cs source. The new calibration is with a ^{90}Sr source. Because ^{90}Sr will be in equilibrium with its ^{90}Y progeny, the instrument also will measure the ^{90}Y. Any ^{90}Sr dispersed into the water supply can be assumed to be in equilibrium with its progeny ^{90}Y (72 hours has already passed since the onset of the event), so the direct beta measurement will be a good approximation of the ^{90}Sr concentration.

Analysis Path

Step 1. The three samples are surveyed upon arrival using a survey meter that has a sliding metal window. The measurements for the three samples yield the following results for gross beta-gamma:

Sample Number	L271	L375	L446	Background
Instrument reading β + γ, cpm	26 ± 3	35 ± 3	85 ± 4	28 ± 3
Instrument reading γ only, cpm	26 ± 2	26 ± 2	29 ± 3	25 ± 2

(Associated uncertainties are 1 sigma.)

The direction from the IC is to assess samples for potential as a source for drinking water. Since the event-specific radionuclide is known (^{90}Sr, Step 2β), the laboratory personnel use flowchart for Scenario 3 to get directly to Step 3β. *It is Day 3, 0830 hours.*

Step 3β1. Sample L271 indicates that it is close to background and apparently has no significant beta emitters based on the gross screen. A 10-mL aliquot is counted for 60 minutes using the LSC yielding a value of 100 pCi/L. Using Table 12 in Appendix VI, an MDC for a 10-mL sample and 60 minute count time is 210 pCi/L (this would be adjusted by the laboratory to its specific counting systems). The ADL for this measurement is 110 pCi/L.[1] Because this result is less than the ADL, its value is less than the MDC. Proceed to Step 4β1. *It is Day 3, 1000 hours.*

Both L375 and L446 yield significant beta and gamma count rates, and after Step 4 should be considered for other analyses if directed by the IC (Step 4β2).

Step 4β1. ^{90}Sr analysis is performed according to Standard Methods Procedure 7500-Sr (see reference on page 9). The final analytical value determined for ^{90}Sr is (1.95 ± 0.38) pCi/L, with an MDC of 0.84 pCi/L. Because this is less than the MCL, proceed to Step 5β1.[2] *It is Day 4, 1400 hours.*

Step 5β1. All other SDWA analyses are performed. The only other radionuclide identified is ^{226}Ra at a concentration of (2.6 ± 0.56) pCi/L, with an MDC of 0.90 pCi/L. *It is Day 4, 2300 hours.*

Step 6β1. The RDL value is 2.0 pCi/L for ^{90}Sr and 1.0 pCi/L for ^{226}Ra. Because ^{90}Sr has an MDC of 0.84 pCi/L, and ^{226}Ra has an MDC of 0.90 pCi/L, MQO requirements for both radionuclides have been met, and the data are deemed validated.

Step 7. The screening results were basically background. The low concentrations of the two radionuclides found are consistent with the background reading on the gross scan, and on the gross LSC analysis (the sum of the ^{90}Sr and ^{226}Ra would yield less than the gross counts background of 28 cpm for the survey meter, and the sum of the ^{90}Sr and ^{226}Ra progeny would yield less than the 100 pCi/L measured with the LSC gross screen).

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[1]UBGR – LBGR = 210 – 0. u_{MR} = 210/3.29 = 64. ADL = MDC – 1.645 × 64 = 105 cpm.

[2]However, additional analyses will need to be done to ensure that MCLs for all radionuclides are met before the water supply is approved for consumption.

Step 8. The sum of the fractions does not need calculation unless tritium or other β and γ emitters are found in the sample. Ra-228 analysis will need to be done also to ensure compliance with the SDWA. [If previous results from this water source are available, this step may be omitted.]

Step 9. The IC is notified that water sample L271 has met the radionuclide requirements of the SDWA. Gross screening of samples L375 and L446 indicated that they contained high levels of radionuclides. Request direction as to whether or not detailed analyses on these sources should be performed.

The time is Day 5, 2400 hours.

Elapsed time from receipt of samples at laboratory: 40 hours.

APPENDIX V. Representative Analytical Processing Times

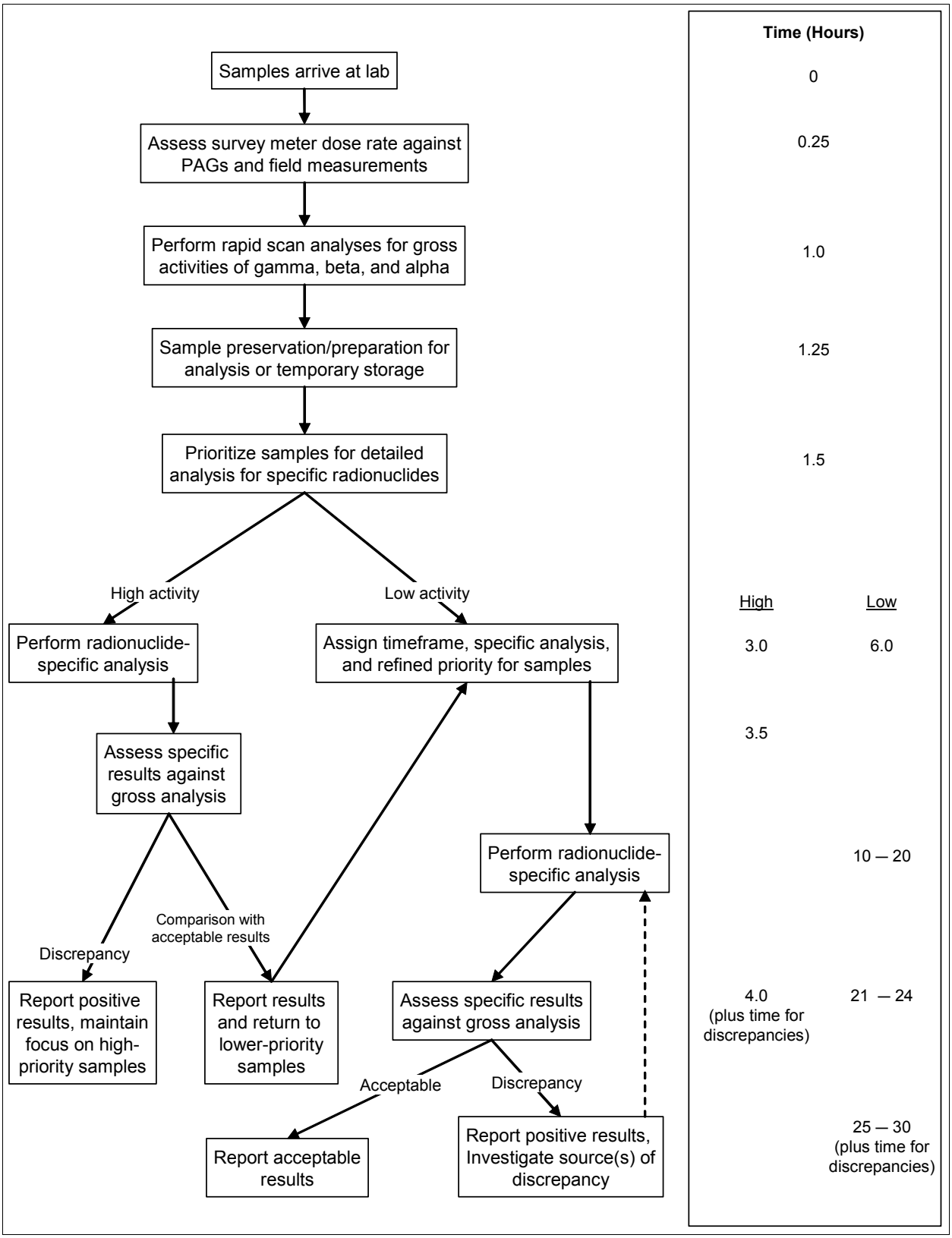

Figure 5 – Approximate Timeframe for Radiochemical Analyses (Radioanalytical Scenario 1)

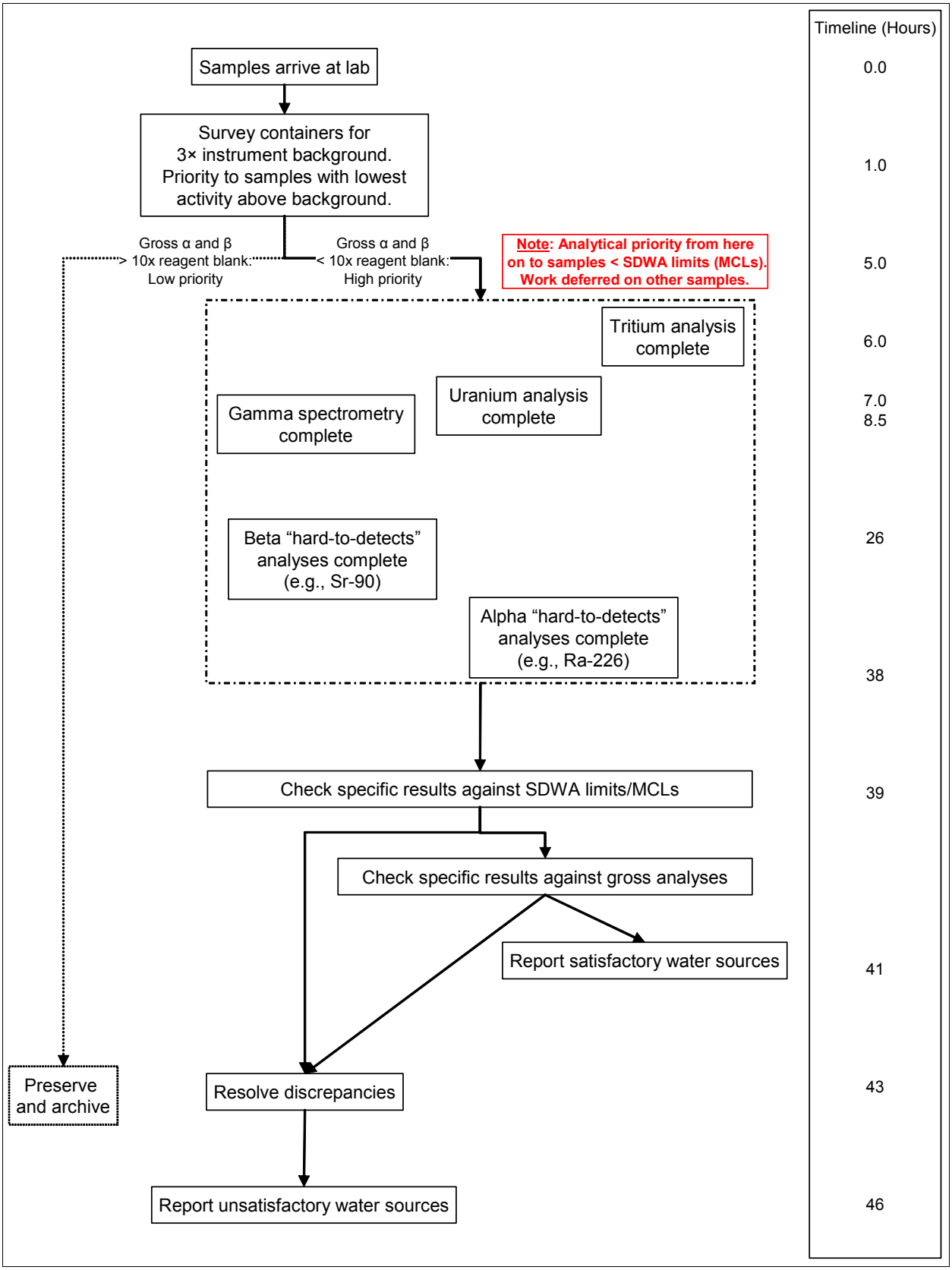

Figure 6 – Approximate Timeframe for Radiochemical Analyses (Radioanalytical Scenario 2)

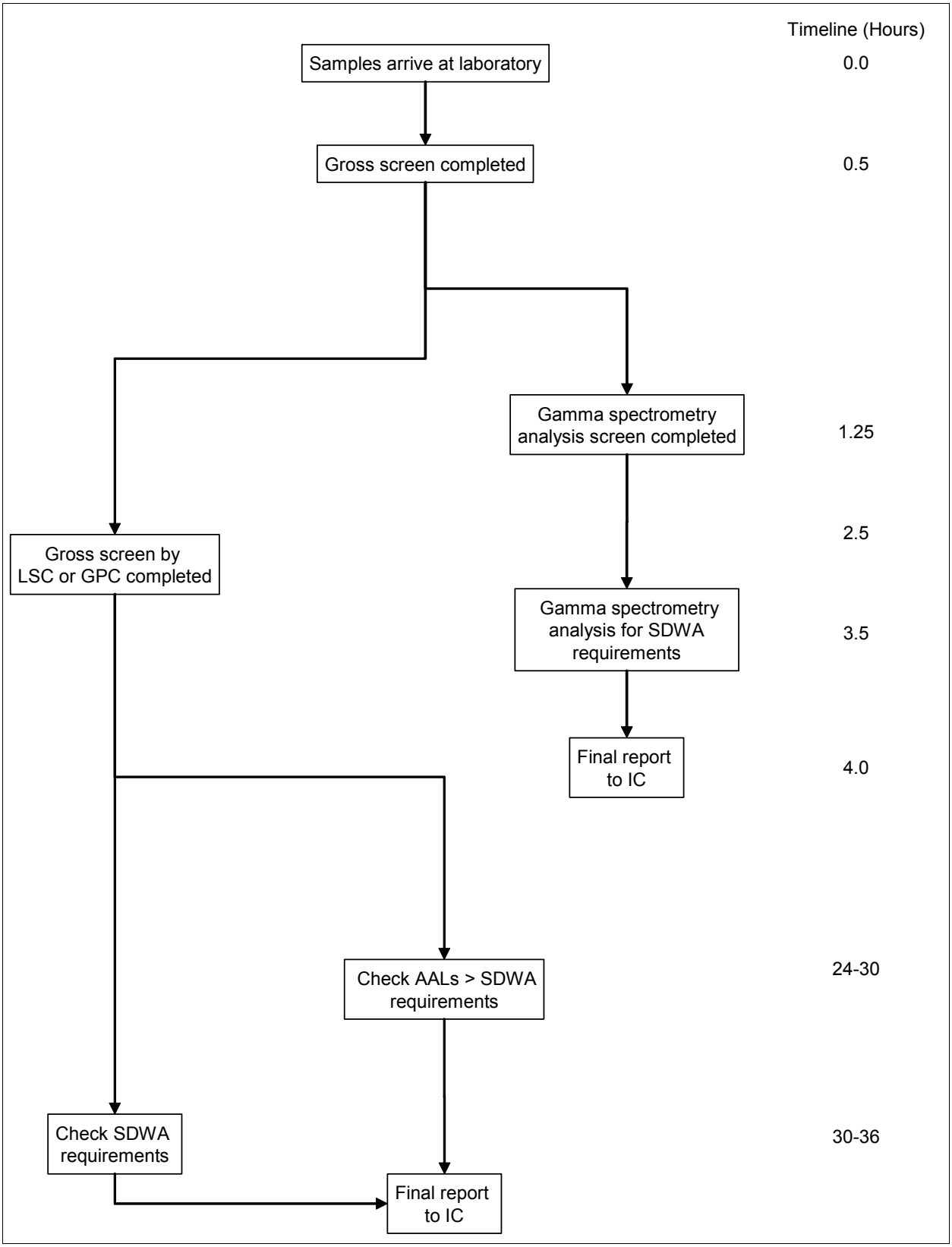

Figure 7 – Approximate Timeframe for Radiochemical Analyses (Radioanalytical Scenario 3)

APPENDIX VI. Establishing DQOs and MQOs for Incident Response Analysis

Three distinct radioanalytical scenarios are presented for water potentially contaminated with radionuclides. The first two assume that the mixture of radionuclides in the sample is unknown. In each scenario there is special emphasis on the implementation of the decision trees presented within that scenario for prioritizing sample processing by the laboratory. This is to support timely decision-making by the IC regarding actions to protect human health for the first two cases, and in the third case to expedite analysis so that suitable drinking water may be used. Specific MQOs are not given for the third radioanalytical scenario because the analytical action levels (AALs) and decision levels (DLs) default to the SDWA requirements (see Tables 7A and 7B). The screening analyses in this scenario are simply used for internal laboratory prioritization.

This appendix covers single-sample screening measurement decisions by the laboratory. The IC may need to make decisions based on the final radionuclide-specific concentrations based on the mean of the set of samples taken from an area. Measurement quality objectives (MQOs) would need to be developed separately for this case. The required method uncertainty (u_{MR}) should be smaller in this case compared to the laboratory's screening decisions, perhaps by a factor of three (See MARLAP Appendix C).

The flowcharts depicted in this document contain decision points. There are three basic symbols on these flowcharts: Squares, which represent activities or tasks; diamonds, which represent decision points; and arrows, which represent flow of control. In these flow diagrams, there are many diamond-shaped decision points. Most often they are of the form shown in Figure 8. This is the general form of a theoretical decision rule as discussed in Step 5 of the data quality objectives (DQO) process. The parameter of interest usually is the "measurand" of the radiochemical analysis being performed (e.g., concentration of a radionuclide, total activity, etc.). The AALs will have been set according to criteria involving the appropriate PAGs or MCLs. The arrows specify the alternative actions to be taken.

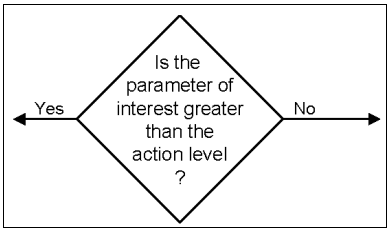

Figure 8 – A Decision Point in a Flowchart

The DQO process[1] may be applied to all programs involving the collection of environmental data with objectives that cover decisionmaking activities. When the goal of the study is to support decisionmaking, the DQO process applies systematic planning and statistical hypothesis testing methodology to decide between alternatives. Data quality objectives can be developed using the Guidance in EPA (2006) *Guidance on Systematic Planning Using the Data Quality Objectives Process (EPA QA/G-4)*. The DQO process is summarized in Figure 9.

Table 8 summarizes the DQO process. From these, MQOs can be established using the guidance in MARLAP. The information in this table should be sufficient to enable the decisionmaker and laboratory to determine the appropriate MQOs. The output should include an AAL, discrimination limit, gray region, null hypothesis, analytical decision level (referred to in MARLAP as "critical

[1] For appropriate samples, AALs and required detection limits are established in Safe Drinking Water Act regulations (see box 13 in Scenario 1 and boxes 4c, 5, 6, 11, and 12b in Scenario 2).

level"), and required method uncertainty at the AAL. A table summarizing DQO process for each decision point diamond can be prepared in advance and summarized as shown in Table 9.

Note that the existence of a decision point diamond implies that Steps 1-4 already have been determined.

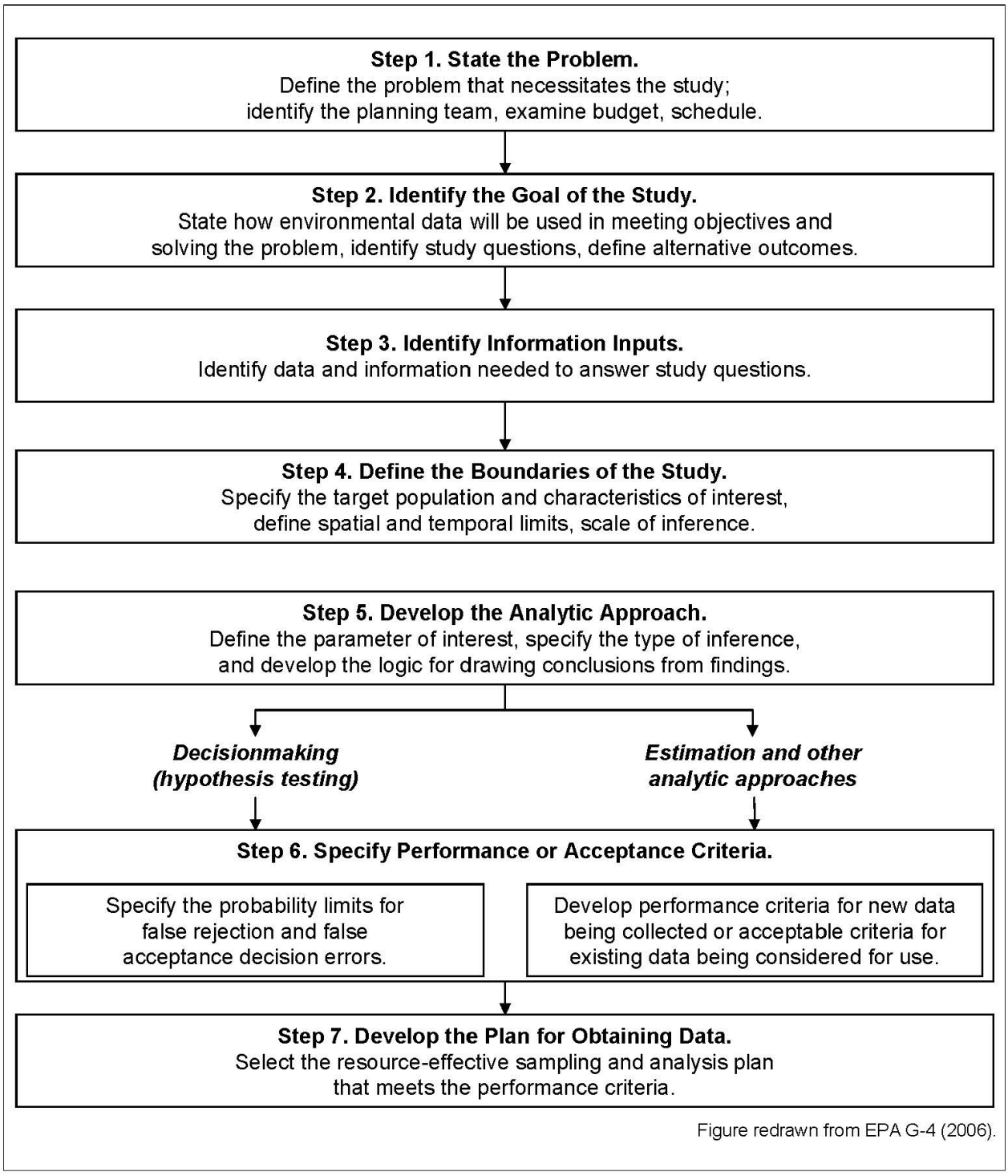

Figure 9 – The Data Quality Objectives Process

TABLE 8A – The DQO Process Applied to a Decision Point

STEP	OUTPUT
Step 1. Define the problem	… with a preliminary determination of the type of data needed and how it will be used; identify decisionmaker.
Step 2. Identify the decision	…among alternative outcomes or actions, and a list of decision statements that address the problem.
Step 3. Identify information needed for the decision	Analytical action levels that will resolve the decision and potential sources for these; information on the number of variables that will need to be collected; the type of information needed to meet performance or acceptance criteria; information on the performance of appropriate sampling and analysis methods.
Step 4. Define the boundaries of the study	Definition of the target population with detailed descriptions of geographic limits (spatial boundaries); detailed descriptions of what constitutes a sampling unit timeframe appropriate for collecting data and making the decision or estimate, together with any practical constraints that may interfere with data collection; and the appropriate scale for decisionmaking or estimation.
Step 5. Develop a decision rule ***This defines the decision point diamond.***	Identification of the population parameters most relevant for making inferences and conclusions on the target population; for decision problems, the "if..., then...else..." theoretical decision rule based upon a chosen AAL.

The theoretical decision rule specified in Step 5 can be transformed into statistical hypothesis tests that are applied to the data. Due to the inherent uncertainty with measurement data, there is some likelihood that the outcome of statistical hypothesis tests will lead to an erroneous conclusion, i.e., a decision error. This is illustrated in Table 8B.

TABLE 8B – Possible Decision Errors

	True Value of the parameter of interest	
Decision Made	**Greater than the AAL**	**Less than the AAL**
Decide that the parameter of interest is greater than the analytical action level	Correct decision	*Decision Error*
Decide that the parameter of interest is less than the analytical action level	*Decision Error*	Correct decision

In order to choose an appropriate null hypothesis (or baseline condition), consider which decision error should be more protected against. Choose the null hypothesis which if falsely rejected would cause the greatest harm. Then the data will need to be convincingly inconsistent with the null hypothesis before it will be rejected, and the probability of this happening (a Type I error) is more easily controlled during the statistical design. Using values from Table 8D, Figures 10 and 11 illustrate these concepts for case (a) and case (b) respectively.

Failing to detect a sample that exceeds the AAL could have consequences to public health. But screening additional samples will slow the overall process and therefore also may impact the public health. The probability that such decision errors occur are defined as the parameters α and β in steps 6.1 and 6.2 in Table 8C. Values of alpha and beta should be set based on the consequences of making an incorrect decision. How these are balanced will depend on the AAL, sample loads, and other factors as specified by the IC.

The most commonly used values of alpha and beta are 5%, although this is by tradition and has no sound technical basis. These values may be used as a default, but should be optimized in Step 7 of the DQO process according to the actual risk of the decision error being considered.

TABLE 8C – The DQO Process Applied to a Decision Point

STEP	OUTPUT
Step 6. Specify limits on decision errors	

Step 6.1 Determine analytical action level (AAL) on the gray region boundary and set baseline condition (null hypothesis, H_0)	Which is considered the worse: decision error (a) deciding that the parameter of interest is less than the AAL when it actually is greater, or (b) deciding that the parameter of interest is greater than the AAL when it actually is less? Case (a) is usually considered to be a conservative choice by regulatory authorities, but this may not be appropriate in every case.
	
	If (a), the AAL defines the upper boundary of the gray region. The null hypothesis is that the sample concentration is above the AAL. (All samples will be assumed to be above the AAL unless the data are convincingly lower.) A desired limit will be set on the probability (α) of incorrectly deciding the sample is below the AAL when the sample concentration is actually equal to the AAL.
	
	If (b), the AAL defines the lower boundary of the gray region. The null hypothesis is that the sample concentration is below the AAL. (All samples will be assumed to be below the AAL unless the data are convincingly higher.) A desired limit will be set on the probability (α) of incorrectly deciding the sample is above the AAL when the sample concentration is actually equal to the AAL.

6.2 Define the discrimination limit (DL)	If (a), the discrimination limit defines the lower boundary of the gray region.[1] It will be a concentration below the AAL where the desired limit will be set on the probability (β) of incorrectly deciding the sample is above the AAL.
	
	If (b), the discrimination limit defines the upper boundary of the gray region.[2] It will be a concentration above the AAL where the desired limit will be set on the probability (β) of incorrectly deciding the sample is below the AAL.

6.3 Define the required method uncertainty at the AAL	According to MARLAP Appendix C, under either case (a) or case (b) above, the recommended required method uncertainty is: $$u_{MR} \leq \frac{UBGR - LBGR}{z_{1-\alpha} + z_{1-\beta}} = \frac{\Delta}{z_{1-\alpha} + z_{1-\beta}}$$ where $z_{1-\alpha}$ and $z_{1-\beta}$ are the $1-\alpha$ and $1-\beta$ quantiles of the standard normal distribution function.
Step 7. Optimize the design for obtaining data	Iterate steps 1–6 to define optimal values for each of the parameters and the measurement method required.

NOTES:

[1] The DL is the point where it is important to be able to distinguish expected signal from the AAL. When one expects background activity, then it might be zero. If one expects activity near the AAL, however, it might be at 90% of the AAL.

[2] The DL is the point where it is important to be able to distinguish expected signal from the AAL. If the AAL is near zero, the DL would define a concentration deemed to be too high to be undetected. Thus, the DL may be set equal to the MDC. If one expects activity near the AAL, however, it might be at 110% of the AAL.

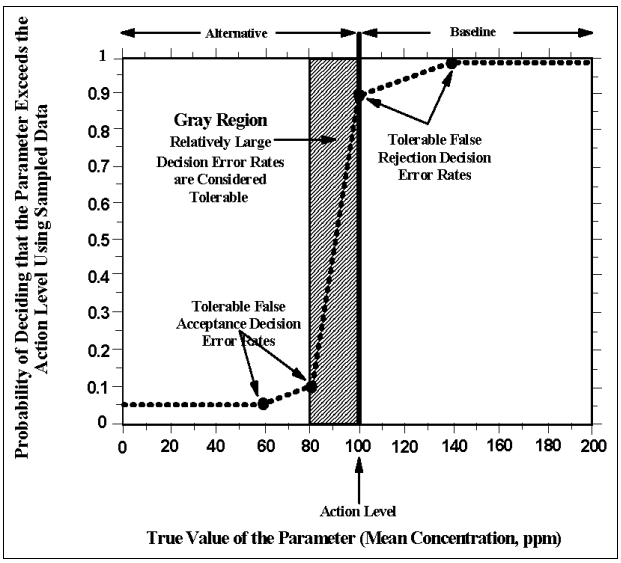

Figure 10 – Example Illustrating Case (a). Baseline Condition (null hypothesis): Parameter Exceeds the AAL

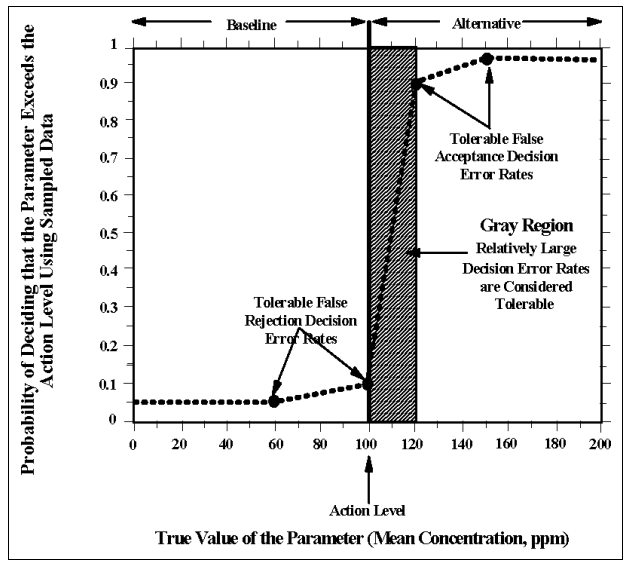

Figure 11 – Example Illustrating Case (b). Baseline Condition (null hypothesis): Parameter Does Not Exceed the AAL

Figures taken from EPA G-4 (2006)

In Figure 10, the AAL = 100, the DL = 80, Δ = 100 – 80 = 20 $\alpha = \beta = 0.1$ and

$$u_{MR} \le \frac{\Delta}{z_{1-\alpha} + z_{1-\beta}} = \frac{20}{1.282 + 1.282} = 7.8.$$

In Figure 11, the AAL = 100, the DL = 120, Δ = 120-100 = 20 $\alpha = \beta = 0.1$ and

$$u_{MR} \le \frac{\Delta}{z_{1-\alpha} + z_{1-\beta}} = \frac{20}{1.282 + 1.282} = 7.8.$$

Table 8D – Values of $z_{1-\alpha}$ (or $z_{1-\beta}$) for Some Commonly Used Values of α (or β)

α or β	$z_{1-\alpha}$ (or $z_{1-\beta}$)
0.001	3.090
0.01	2.326
0.025	1.960
0.05	1.645
0.10	1.282
0.20	0.842
0.30	0.524
0.50	0.000

The concentration that indicates the division between values leading to rejecting the null hypothesis and those that do not is termed the "critical level." Possible values of the concentration can be divided into two regions, the acceptance region and the rejection region. If the value of the concentration comes out to be in the acceptance region, the null hypothesis being tested is not rejected. If the concentration falls in the rejection region, the null hypothesis is rejected. The set of values of a statistic that will lead to the rejection of the null hypothesis tested is called the critical region. Critical region is a synonym for rejection region.

In the context of analyte detection, the *critical value* (see MARLAP Attachment 3B.2) is the minimum measured value (e.g., of the instrument signal or the *analyte* concentration) required to give confidence that a positive (nonzero) amount of *analyte* is present in the material analyzed. The critical value is sometimes called the *critical level*.

In case (a), the critical value will be UBGR $- z_{1-\alpha} u_{\mathrm{M}}$, where u_{M} is its combined standard uncertainty of the measurement result, x. Only measurement results less than the critical value will result in rejecting the null hypothesis that the true concentration is greater than the AAL.

In case (b), the critical value will be LBGR $+ z_{1-\alpha} u_{\mathrm{M}}$, where u_{M} is its combined standard uncertainty of the measurement result, x. Only measurement results greater than the critical value will result in rejecting the null hypothesis that the true concentration is less than the AAL. This process can be completed for each diamond in each flowchart to fill in Table 12. In these tables, all values have been rounded to 2 significant figures.

In the following tables, MQOs were determined for screening using a discrimination level of zero and Type I and Type II error rates of alpha = beta = 0.05. These are the MQOs usually associated with developing MDCs and result in a relative method uncertainty of 30% at the AAL, and an ADL value of 0.5 times the AAL.

For radionuclide specific measurements, the requirements are more stringent, using a discrimination level of one-half the AAL and Type I and Type II error rates of alpha = 0.01 with beta = 0.05. This results in a relative method uncertainty of 13% at the AAL and an ADL value of 0.71 times the AAL. Note that gamma spectrometric measurements using an HPGe are always radionuclide specific, and therefore, have the more stringent MQOs.

TABLE 9A – DQOs and MQOs for Radioanalytical Scenario 1. Prioritization Decisions Based on Screening[7] (Gross α, β, or γ Measurements)

Measurement Rectangle	Decision Point Diamond	Type of Analysis, α, β, or γ	Analytical AL (pCi/L)	Null Hypothesis H_0 Choose > AAL or < AAL i.e., case (a) or case (b)	DL DL < AAL in case (a) and DL > AAL in case (b)	Δ = UBGR-LBGR	Type I error rate α	Type II error rate β	u_{MR}	φ_{MR} [6]	RDL or MDC	Analytical Decision Level (Critical Level) (pCi/L)	Source of AAL
	1a	γ[1]	58,000	a	0	58,000	0.05	0.05	18,000	0.30	58,000	29,000	500 mrem ^{137}Cs
2,7	3,8	α	2,000	a	0	2,000	0.05	0.05	610[2, 3]	0.30		1,000	500 mrem ^{241}Am
2,7	9	α	400	a	0	400	0.05	0.05	120[3]	0.30		200	100 mrem ^{241}Am
2,7	3,8	β	12,000	a	0	12,000	0.05	0.05	3,600[3]	0.30		6,000	500 mrem ^{90}Sr
2,7	9	β	2,400	a	0	2,400	0.05	0.05	720[3]	0.30		1200	100 mrem ^{90}Sr
2,7	3,8	γ	33,000	a	16,500	16,500	0.01	0.05	4,100[3]	0.13		23,000	500 mrem ^{60}Co
2,7	9	γ	6,600	a	3,300	3,300	0.01	0.05	830[3]	0.13		4,600	100 mrem ^{60}Co
	11[4]			a									
12	13	α	15	a							3	15	SDWA
12	13	β	50	a							5	50	SDWA
	15[5]												

Notes:

[1] Using survey instrument calibrated to ^{137}Cs on contact in the recommended geometry.

[2] $u_{MR} \le \dfrac{\Delta}{z_{1-\alpha} + z_{1-\beta}} = \dfrac{2000}{1.645 + 1.645} = \dfrac{2000}{3.29} \approx 610$

[3] Diamond 9 is the limiting decision criterion.

[4] Mathematically computed from data obtained earlier.

[5] Based on professional judgment from data obtained earlier. The comparison made is based on the MQOs established for the screening analyses and the individual radionuclide analyses. The acceptability of this measurement will vary widely based on the actual radionuclides in the sample and the radionuclides used to calibrate the screening instruments. Thus it will be incumbent on the laboratory staff to assess the agreement of these numbers. Guidance given in the document is a ratio range of *approximately* 0.5 to 2.0.

[6] The value for φ_{MR} (relative required method uncertainty) is determined by dividing the value of u_{MR} by the AAL (fourth column in this table).

[7] Values for gamma analysis assume radionuclide-specific analyses using an HPGe. If a gamma detector of lower resolution is used, the screening error rates for gamma analysis should be changed to that of the alpha and beta analysis.

TABLE 9B – DQOs and MQOs for Scenario 1. Values Reported Externally Based on Radionuclide-Specific Measurements

Measurement Rectangle	Decision Point Diamond	Type of Analysis, α, β, or γ	Analytical AL (pCi/L)	Null Hypothesis H_0 Choose > AAL or < AAL i.e., case (a) or case (b)	DL DL < AAL in case (a) and DL > AAL in case (b)	Δ = UBGR-LBGR	Type I error rate α	Type II error rate β	u_{MR}	φ_{MR} [2]	RDL or MDC	Analytical Decision Level (Critical Level) (pCi/L)	Source of AAL
4		α	See Tables 10A and 10B	a	0.5 AAL	0.5 AAL	0.01	0.05	AL/8	0.13		0.71×AAL[1]	100 mrem AAL
5		β		a	0.5 AAL	0.5 AAL	0.01	0.05	AL/8	0.13		0.71×AAL	100 mrem AAL
6		γ		a	0.5 AAL	0.5 AAL	0.01	0.05	AL/8	0.13		0.71×AAL	100 mrem AAL
10		α		a	0.5 AAL	0.5 AAL	0.01	0.05	AL/8	0.13		0.71×AAL	100 mrem AAL
10		β γ		a	0.5 AAL	0.5 AAL	0.01	0.05	AL/8	0.13		0.71×AAL	100 mrem AAL
14		α		a	0.5 AAL	0.5 AAL	0.01	0.05	AL/8	0.13		0.71×AAL	100 mrem AAL
14		β γ		a	0.5 AAL	0.5 AAL	0.01	0.05	AL/8	0.13		0.71×AAL	100 mrem AAL

Note:

[1] In case (a), the critical value is UBGR – $z_{1-\alpha}\, u_M$ = AAL – $z_{1-0.01}$ [$\Delta/(z_{1-0.01} + z_{1-0.05})$] = AAL – 2.326[(AAL–0.5 AAL)/(2.326 + 1.645)]
= AAL – 2.326(AAL / 8) ≈ 0.71 AAL. Specific values for the ADL are listed in Tables 6A or 6B.

[2] The value for φ_{MR} (relative required method uncertainty) is determined by dividing the value of u_{MR} by the AAL (fourth column in this table).

TABLE 10A – Derived Water Concentrations (DWC) Corresponding to α-Emitting Radionuclide Analytical Action Levels

Radionuclide	Half-Life	Additional Emissions	pCi/L	
			500-mrem AAL [1] [2]	100-mrem AAL [1] [2] [3]
Gross α Screen [5]	–	–	2.0×10^3	400
Am-241	432.2 y	γ	2.0×10^3	400
Cm-242	162.8 d		1.4×10^4	2.8×10^3
Cm-243	29.1 y	γ	2.5×10^3	500
Cm-244	18.10 y		2.9×10^3	580
Np-237 [4]	2.144×10^6 y	γ	3.9×10^3	780
Po-210	138.4 d		130	26
Pu-238	87.7 y		1.8×10^3	360
Pu-239	2.411×10^4 y		1.7×10^3	340
Pu-240	6.564×10^3 y		1.7×10^3	340
Ra-226 [4]	1.600×10^3 y	γ DP	910	180
Th-228 [4]	1.912 y	γ DP	2.6×10^3	520
Th-230	7.538×10^4 y		1.8×10^3	360
Th-232	1.405×10^{10} y	γ DP	1.6×10^3	320
U-234	2.455×10^5 y	γ DP	6.3×10^3	1300
U-235	7.038×10^8 y	γ DP	6.6×10^3	1300
U-238	4.468×10^9 y	γ DP	7.0×10^3	1.4×10^3

Notes:

The half-lives of the nuclides are given in years (y) or days (d). DP refers to "decay products."

[1] Values are based on the dose conversion factors in Federal Guidance Report No.13, CD Supplement, 5-year-old child and the 50th percentile of water consumption.

[2] 365-day intake.

[3] The-100 mrem AAL values were obtained by dividing 500-mrem PAG DWC values by 5. AALs have been rounded to 2 significant figures.

[4] Includes decay products originating from the ^{226}Ra or ^{228}Th in the body. Used only to calculate the concentration (pCi/L) or dose from ^{226}Ra or ^{228}Th in the body.

[5] The AAL and associated u_{MR} and ADL values for ^{241}Am are used as the default for gross alpha screening analysis.

TABLE 10B – Derived Water Concentrations (DWC) Corresponding to β-Emitting Radionuclide AALs

Radionuclide	Emission Type	Half-Life	pCi/L	
			500-mrem AAL [1] [2]	100-mrem AAL [1] [2] [3]
Beta Gamma Screen [4]	β	–	5.8×10^4	1.2×10^4
Ac-227DP	β (α DP)	21.77 y	1.1×10^3	220
Ce-141	βγ	32.51 d	2.2×10^5	4.4×10^4
Ce-144	βγ	284.9 d	2.9×10^4	5.8×10^3
Co-57	γ	271.1 d	6.3×10^5	1.3×10^5
Co-60	βγ	5.270 y	3.3×10^4	6.6×10^3
Cs-134	βγ	2.065 y	4.3×10^4	8.6×10^3
Cs-137	βγ	30.07 y	5.8×10^4	1.2×10^4
H-3	weak β	12.32 y	7.7×10^6	1.5×10^6
I-125	γ	59.40 d	1.3×10^4	2.6×10^3
I-129	βγ	1.57×10^7 y	3.3×10^3	660
I-131	βγ	8.021 d	5.4×10^3	1.1×10^3
Ir-192	βγ	73.83 d	1.2×10^5	2.4×10^4
Mo-99	β γ (γ DP)	65.94 h	3.2×10^5	6.4×10^4
P-32	β	14.26 d	5.9×10^4	1.2×10^4
Pd-103	γ	16.99 d	7.8×10^5	1.6×10^5
Pu-241	β	14.29 y	1.0×10^5	2.0×10^4
Ra-228	β (γ DP)	5.75 y	160	32
Ru-103	βγ	39.26 d	2.3×10^5	4.6×10^4
Ru-106	βγ	373.6 d	2.2×10^4	4.4×10^3
Se-75	γ	119.8 d	6.7×10^4	1.3×10^4
Sr-89	β	50.53 d	6.3×10^4	1.3×10^4
Sr-90	β	28.79 y	1.2×10^4	2.4×10^3
Tc-99	βγ	2.11×10^5 y	2.4×10^5	4.8×10^4

Notes:
The half-lives of the nuclides are given in years (y), days (d), or hours (h). DP refers to "decay products."
[1] Values are based on the dose conversion factors in Federal Guidance Report No.13, CD Supplement, 5-year-old child and the 50th percentile of water consumption.
[2] 365-day intake.
[3] The 100-mrem AAL values were obtained by dividing 500-mrem PAG DWC values by 5. AALs have been rounded to 2 significant figures.
[4] The AAL and associated u_{MR} and ADL values for ^{137}Cs are used as the defaults for initial beta gamma screening analysis on sample bottle (Step 1 in Radioanalytical Scenarios 1 and 2). The AAL and associated u_{MR} and ADL values for ^{60}Co concentration are used as defaults for gross gamma measurements thereafter (see text). The AAL and associated u_{MR} and ADL values for ^{90}Sr are the defaults used for gross beta screening.

Several nuclides in Table 10B decay by electron capture. These radionuclides cannot be detected using gross β analysis. The electron capture decay leads to characteristic X-rays of the progeny nuclide. The most effective way to detect the X-rays from these electron-capture-decay radionuclides is either with a low-energy photon detector (LEPD) or a reverse electrode germanium detector (N-type semiconductor detector). The lower range of energy with these detectors is about 10 keV.

TABLE 11A – DQOs and MQOs for Scenario 2.
Internal Lab Prioritization Decisions Based on Screening
(Gross α, β, or γ Measurements)

Measurement Rectangle	Decision Point Diamond	Type of Analysis, α, β, or γ	Analytical AL (pCi/L)	Null Hypothesis H_0 Choose > AAL or < AAL i.e. case (a) or case (b)	DL DL < AAL in case (a) and DL > AAL in case (b)	Δ = UBGR-LBGR	Type I error rate α	Type II error rate β	u_{MR}	φ_{MR} [3]	RDL or MDC	Analytical Decision Level (Critical Level) (pCi/L)	Source of AAL
	1	γ[1]	12,000	a	0	12,000	0.05	0.05	3,600	0.30	12,000	6,000	100 mrem ^{137}Cs AAL
2a	2b	α	210	a	0	210	0.05	0.05	64	0.30	210	110	LSC MDC 5mL 10 min[2]
2a	2b	β	820	a	0	820	0.05	0.05	250	0.30	820	410	LSC MDC 5mL 10 min[2]
14a	14b	α	210	a	0	210	0.05	0.05	64	0.30	210	110	LSC MDC 5mL 10 min[2]
14a	14b	β	820	a	0	820	0.05	0.05	250	0.30	820	410	LSC MDC 5m: 10 min[2]
3	5	β	50								5	50	SDWA
3	6	α	15								3	15	SDWA

Notes:
[1] Using survey instrument calibrated to ^{137}Cs on contact.
[2] See Table 12.
[3] The value for φ_{MR} is determined by dividing the value of u_{MR} by the AAL (fourth column in this table).

TABLE 11B – DQOs and MQOs for Scenario 2.
Values Reported Externally Based on Radionuclide-Specific Measurements

Measurement Rectangle	Decision Point Diamond	Type of Analysis, α, β, or γ	Analytical AL (pCi/L)	Null Hypothesis H_0 Choose > AAL or < AAL i.e. case (a) or case (b)	DL DL < AAL in case (a) and DL > AAL in case (b)	Δ = UBGR-LBGR	Type I error rate α	Type II error rate β	u_{MR}	φ_{MR}	RDL	Analytical Decision Level (Critical Level) (pCi/L)	Source of AAL
7	11	β	See Tables 7A and 7B								See Tables 7A and 7B		SDWA
8	11	α											SDWA
9	11	γ											SDWA
4a	4b, 4c	^{3}H	20,000								1,000	20,000	SDWA
12a	12b	U	20[1]								0.3	20	SDWA

Note:
[1] 20 pCi/L = 30 ppb U. The measurement of uranium can be based on mass or activity using appropriate conversion factors.

Estimates of nominal *a priori* minimum detectable concentrations (MDC) for two commonly used gross alpha and beta screening methods, using liquid scintillation and gas proportional counting, have been summarized in Table 12. The table provides estimates of MDCs as a function of sample aliquant volume and sample

counting times. The MDCs were calculated using the working expressions provided by Currie[1], assuming paired observations having equal counting times for background and sample measurements and Type I and II error probabilities of 5%. The table notes provide the typical modern instrument detector efficiencies and background count rates used to calculate the MDC values. Critical levels (L_C) are one-half the MDCs.

TABLE 12 – Minimum Detection Concentration Values for Various Counting Times and Sample Volumes

Liquid Scintillation Counting

Emission Type	Alpha	Alpha	Alpha	Alpha	Alpha	Beta	Beta	Beta	Beta	Beta
Volume (mL)	10	10	10	10	10	10	10	10	10	10
Count Time (m)	1	5	10	30	60	1	5	10	30	60
MDC (pCi/L)	590	210	140	77	53	1,720	730	510	290	210
L_C (pCi/L)	295	105	120	38.5	26.5	860	365	255	145	105

Emission Type	Alpha	Alpha	Alpha	Alpha	Alpha	Beta	Beta	Beta	Beta	Beta
Volume (mL)	5	5	5	5	5	5	5	5	5	5
Count Time (m)	1	5	10	30	60	1	5	10	30	60
MDC (pCi/L)	880	320	210	110	79	2,760	1,170	820	470	330
L_C (pCi/L)	440	160	105	55	39.5	1,380	585	410	235	115

Assumptions for 5-mL sample: alpha detector efficiency = 0.8; alpha background cpm = 1.2; beta detector efficiency = 1.0; beta background cpm = 36

Gas Proportional Counting

Emission Type	Alpha	Alpha	Alpha	Alpha	Alpha	Beta	Beta	Beta	Beta	Beta
Volume (mL)	10	10	10	10	10	10	10	10	10	10
Count Time (m)	1	5	10	30	60	1	5	10	30	60
MDC (pCi/L)	1,880	540	330	160	110	1,230	450	300	160	110
L_C (pCi/L)	940	270	165	80	55	615	225	150	80	105

Emission Type	Alpha	Alpha	Alpha	Alpha	Alpha	Beta	Beta	Beta	Beta	Beta
Volume (mL)	5	5	5	5	5	5	5	5	5	5
Count Time (m)	1	5	10	30	60	1	5	10	30	60
MDC (pCi/L)	3,770	1,080	660	320	210	2,470	900	600	330	230
L_C (pCi/L)	1,885	540	330	160	105	1,235	450	300	165	115

Assumptions: alpha detector efficiency = 0.10; alpha background cpm = 0.10; beta detector efficiency = 0.30; beta background cpm = 1.4

[1]Currie, Lloyd. 1968. "Limits for Qualitative Detection and Quantitative Determination: Application to Radiochemistry." Analytical Chemistry 40(3): 586-593.

APPENDIX VII. Glossary

***accuracy*:** The closeness of a measured result to the true value of the quantity being measured. Various recognized authorities have given the word "accuracy" different technical definitions, expressed in terms of bias and imprecision. Following MARLAP, this document avoids all of these technical definitions and uses the term "accuracy" in its common, ordinary sense.

aerosol: A suspension of fine solid or liquid particles within a gaseous matrix (usually air).

***aliquant*:** A representative portion of a homogeneous *sample* removed for the purpose of analysis or other chemical treatment. The quantity removed is not an evenly divisible part of the whole sample. An aliquot, by contrast, is an evenly divisible part of the whole.

***analyte*:** See *target analyte*.

analytical action level (AAL): The value of a quantity that will cause the decisionmaker to choose one of the alternative actions. The *analytical action level* may be a derived concentration level (such as the *derived water concentration* in this document), background level, release criteria, regulatory decision limit, etc. The AAL is often associated with the type of media, *target analyte*, and concentration limit. Some AALs, such as the release criteria for license termination, are expressed in terms of dose or risk. MARLAP uses the term "action level." See *total effective dose equivalent (TEDE)*.

analytical decision level (ADL): The minimum measured value for the radionuclide concentration in a sample that indicates the amount of radionuclide present is equal to or greater than the *analytical action level* at a specified *Type II error* rate (assumes that *method uncertainty* requirements have been met). Any measurement result equal to or greater than the applicable ADL is considered to have exceeded the corresponding *analytical action level*. MARLAP uses the term "*critical level*."

***background (instrument)*:** Radiation detected by an instrument when no *source* is present. The background radiation that is detected may come from radionuclides in the materials of construction of the detector, its housing, its electronics, and the building, as well as the environment and natural radiation.

***background level*:** A term that usually refers to the presence of radioactivity or radiation in the environment. From an analytical perspective, the presence of background radioactivity in samples needs to be considered when clarifying the radioanalytical aspects of the decision or study question. Many radionuclides are present in measurable quantities in the environment.

***bias (of a measurement process)*:** A persistent deviation of the mean measured result from the true or accepted reference value of the quantity being measured, which does not vary if a measurement is repeated.

***blank (analytical or method)*:** A *sample* that is assumed to be essentially free of the *target analyte* (the "unknown"), which is carried through the radiochemical preparation, analysis, mounting, and measurement process in the same manner as a routine sample of a given matrix.

***calibration*:** The set of operations that establishes, under specified conditions, the relationship between values indicated by a measuring instrument or measuring system, or values represented by a material measure, and the corresponding known value of a parameter of interest.

***calibration source*:** A prepared *source*, made from a *certified reference material*, that is used for calibrating instruments.

***certified reference material*:** A radioactive material, accompanied by an uncertainty at a stated level of confidence, with one or more values certified by a procedure that establishes its traceability to accepted standard values. A "standard reference material" is a certified reference material issued by the National Institute of Standards and Technology (NIST) in the United States. NIST certifies a standard reference material for specific chemical or physical properties and issues it with a certificate that reports the results of the characterization and indicates the intended use of the material.

***chain of custody*:** Procedures that provide the means to trace the possession and handling of a sample from collection to data reporting.

***check source*:** A material used to validate the operability of a radiation measurement device, sometimes used for instrument quality control. See *source, radioactive*.

critical level: Termed *analytical decision level* in this document in the context of evaluating sample results relative to an *analytical action level*. In the context of analyte detection, *critical level* means the minimum measured value (e.g., of the instrument signal or the radionuclide concentration) that indicates a positive (nonzero) amount of a radionuclide is present in the material within a specified probable error. The critical level is sometimes called the *critical value* or *decision level*.

***data quality objective* (*DQO*)**: Qualitative and quantitative statements that clarify the study objectives, define the most appropriate type of data to collect, determine the most appropriate conditions from which to collect the data, and specify tolerable limits on decision error rates. Because DQOs will be used to establish the quality and quantity of data needed to support decisions, they should encompass the total *uncertainty* resulting from all data collection activities, including analytical and sampling activities.

derived radionuclide concentration (DRC): General application term used in discussions involving both of the terms *derived air concentration* and *derived water concentration*.

derived water concentration (DWC): The concentration of a radionuclide, in pCi/L, that would result in exposure to a specified dose level. Generally refers to a *protective action guide* or other specified dose- or risk-based factor related to an *analytical action level*. In this document, for example, the "500-mrem DWC for ^{239}Pu" is the concentration of ^{239}Pu, in pCi/L, that would result in an exposure of 500 mrem and would refer to the 500-mrem PAG. The DWC is radionuclide-specific.

discrimination limit (DL): The DL is the point where it is important to be able to distinguish expected signal from the *analytical action level*. The boundaries of the *gray region*.

***dose equivalent*:** Quantity that expresses all radiations on a common scale for calculating the effective absorbed dose. This quantity is the product of absorbed dose (*grays* (Gy) or rads) multiplied by a quality factor and any other modifying factors (MARSSIM, 2000). The quality factor adjusts the absorbed dose because not all types of ionizing radiation create the same effect on human tissue. For example, a dose equivalent of one *sievert* (Sv) requires 1 Gy of beta or gamma radiation, but only 0.05 Gy of alpha radiation or 0.1 Gy of neutron radiation. Because the sievert is a large unit, radiation doses often are expressed in millisieverts (mSv). See *total effective dose equivalent* and *roentgen*.

***gray (Gy)*:** The International System of Units (SI) unit for absorbed radiation dose. One gray is 1 joule of energy absorbed per kilogram of matter, equal to 100 *rad*. See *sievert*.

***gray region*:** The range of possible values in which the consequences of decision errors are relatively minor. Specifying a gray region is necessary because variability in the analyte in a population and imprecision in the measurement system combine to produce variability in the data such that the decision may be "too close to call" when the true value is very near the *analytical action level*. The *gray region* establishes the minimum distance from the *analytical action level* where it is most important to control *Type II decision errors*.

***incident of national significance (INS)*:** An actual or potential high-impact event that requires a coordinated and effective response by and appropriate combination of federal, state, local, tribal, nongovernmental, or private-sector entities in order to save lives and minimize damage, and provide the basis for long-term community recovery and mitigation activities.

***measurement quality objective* (*MQO*):** The analytical data requirements of the *data quality objectives*, which are project- or program-specific and can be quantitative or qualitative. These analytical data requirements serve as measurement performance criteria or objectives of the analytical process. MARLAP refers to these performance objectives as MQOs. Examples of quantitative MQOs include statements of required analyte detectability and the *uncertainty* of the analytical protocol at a specified radionuclide concentration, such as the *analytical action level*. Examples of qualitative MQOs include statements of the required specificity of the analytical protocol (e.g., the ability to analyze for the radionuclide of interest (or *target analyte*) given the presence of interferences).

***method uncertainty*:** The predicted *uncertainty* of the result that would be measured if the method were applied to a hypothetical laboratory *sample* with a specified analyte concentration. Although individual measurement uncertainties will vary from one measured result to another, the *required method uncertainty* is a target value for the individual measurement uncertainties and is an estimate of uncertainty before the sample is actually measured. See also *uncertainty*, *required method uncertainty*, and *relative required method uncertainty*.

***method validation*:** The demonstration that the method selected for the analysis of a particular analyte in a given matrix is capable of providing analytical results to meet the project's *measurement quality objectives* and any other requirements in the analytical protocol specifications.

***minimum detectable concentration (MDC)*:** An estimate of the smallest true value of the analyte concentration that gives a specified high probability of detection.

***nuclide-specific analysis*:** Radiochemical analysis performed to isolate and measure a specific radionuclide.

***null hypothesis (H_0)*:** One of two mutually exclusive statements tested in a statistical *hypothesis test* (compare with alternative hypothesis). The null hypothesis is presumed to be true unless the test provides sufficient evidence to the contrary, in which case the *null hypothesis* is rejected and the alternative hypothesis (H_1) is accepted.

***performance evaluation (PE) program*:** A laboratory's participation in an internal or external program of analyzing proficiency-testing samples appropriate for the analytes and matrices under consideration (i.e., PE program traceable to a national standards body, such as NIST). Reference-material samples used to evaluate the performance of the laboratory are called performance-evaluation or proficiency-testing samples or materials. See *certified reference material*.

***precision*:** The closeness of agreement between independent test results obtained by applying the experimental procedure under stipulated conditions. Precision may be expressed as the standard deviation. Conversely, imprecision is the variation of the results in a set of replicate measurements.

protective action guide (PAG): The radiation dose to individuals in the general population that warrants protective action following a radiological event. In this document, PAGs limit the projected radiation doses for different exposure periods: not to exceed 2-rem *total effective dose equivalent (TEDE)* during the first year, 500-mrem TEDE during the second year, or 5 rem over the next 50 years (including the first and second years of the incident). See *total derived water concentration* and *analytical action level*.

***quality assurance (QA)*:** An integrated system of management activities involving planning, implementation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected. Quality assurance includes *quality control*.

***quality control (QC)*:** The overall system of technical activities that measures the attributes and performance of a process, item, or service against defined standards to verify that they meet the stated requirements established by the project; operational techniques and activities that are used to fulfill requirements for quality. This system of activities and checks is used to ensure that measurement systems are maintained within prescribed limits, providing protection against out-of-control conditions and ensuring that the results are of acceptable quality.

reference material: See *certified reference material*.

***rem*:** The common unit for the effective or equivalent dose of radiation received by a living organism, equal to the actual dose (in rads) multiplied by a factor representing the danger of the radiation. Rem is an abbreviation for "roentgen equivalent man," meaning that it measures the biological effects of ionizing radiation in humans. One rem is equal to 0.01 Sv. See *sievert* and *dose equivalent*.

relative required method uncertainty **(φ_{MR}):** The *required method uncertainty* divided by the *analytical action level*. The relative required method uncertainty is applied to radionuclide concentrations above the *analytical action level*. A key *measurement quality objective*.

required method uncertainty **(u_{MR}):** *Method uncertainty* at a specified concentration. A key *measurement quality objective*. See also *relative required method uncertainty*.

roentgen (R): A unit of exposure to ionizing radiation. It is that amount of gamma rays or X-rays required to produce ions carrying one electrostatic unit of electrical charge in one cubic centimeter of dry air under standard conditions. The unit of exposure rate is roentgens per hour (R/h). For environmental exposures, the typical units are microroentgens per hour (μR/h), or 10^{-6} R/h. In SI units, 1 R = 2.58×10^{-4} C/kg (coulombs per kilogram).

sample**:** (1) A portion of material selected from a larger quantity of material. (2) A set of individual samples or measurements drawn from a population whose properties are studied to gain information about the entire population.

screening method**:** An economical gross measurement (alpha, beta, gamma) used in a tiered approach to method selection that can be applied to *analyte* concentrations below an *analyte* level in the *analytical protocol specifications* or below a fraction of the specified *action level.*

sievert (Sv)**:** The SI unit for the effective dose of radiation received by a living organism. It is the actual dose received (*grays* in SI or rads in traditional units) times a factor that is larger for more dangerous forms of radiation. One Sv is 100 *rem*. Radiation doses are often measured in mSv. An effective dose of 1 Sv requires 1 gray of beta or gamma radiation, but only 0.05 Gy of alpha radiation or 0.1 Gy of neutron radiation.

source, radioactive**:** A quantity of material configured for radiation measurement.

source term radionuclide**:** A radionuclide that is a significant contaminant in an environmental sample and results in dose contributions that will be important in decisionmaking.

sum of fractions: A calculated value to determine whether the summed contributions to dose by all radionuclides in a sample, divided by their respective dose limits, exceeds 1.0. For purposes of this calculation, the actual *analytical action level* (*derived water concentration* or *protective action guide*) is used rather than an *analytical decision level*.

swipes**:** A filter pad used to determine the level of general radioactive contamination when it is wiped over a specific area, about 100 cm^2 in area. Also called smears or wipes.

target analyte**:** A radionuclide on the list of radionuclides of interest or a radionuclide of concern for a project.

total effective dose equivalent**:** The sum of the effective dose equivalent (for external exposure) and the committed effective dose equivalent (for internal exposure), expressed in units of Sv or rem. See *dose equivalent*.

***Type I decision error*:** In a hypothesis test, the error made by rejecting the null hypothesis when it is true. A Type I decision error is sometimes called a "false rejection" or a "false positive."

***Type II decision error*:** In a hypothesis test, the error made by failing to reject the null hypothesis when it is false. A Type II decision error is sometimes called a "false acceptance" or a "false negative."

***uncertainty*:** A parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand. See *method uncertainty*.