NUREG-1575, Revision 2
EPA-402-B-26-001
DOE/EHSS-1000

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MULTI-AGENCY RADIATION SURVEY AND SITE INVESTIGATION MANUAL (MARSSIM)

Appendices

Revision 2 March 2026

CONTENTS

TABLES

FIGURES

APPENDIX A
EXAMPLE OF MARSSIM APPLIED TO A FINAL STATUS SURVEY

A.1 Introduction

This appendix presents a relatively simple example of a final status survey (FSS). Portions of this example appear earlier in **Chapter 5** and **Chapter 8**. This appendix highlights the major steps in implementing an FSS and gathering information needed to prepare a report. The report's format will vary with the requirements of the regulatory agency and the complexity of the site and the FSS. Larger projects will likely result in longer FSS reports, where tables of contents, lists of figures, lists of tables, and appendices and annexes will be helpful. For smaller projects, some of the items listed above may not be necessary. In either instance, the planning team should[1] work with the regulatory agency early in the project to establish expectations related to required documentation and the format of the FSS report(s).

The FSS Checklist given at the end of **Section 5.3.11** serves as a general outline for this appendix, although not every point is discussed in detail. Chapters and sections of MARSSIM covering particular points are referenced at each step. This example presents detailed calculations for a single Class 1 survey unit.

A.2 Historical Information

(**Chapter 3**)

The Specialty Source Manufacturing Company produced low-activity encapsulated sources of radioactive material for use in classroom educational projects, instrument calibration, and consumer products. The manufacturing process—conducted between 1978 and 1993—involved combining a liquid containing a known quantity of the radioactive material with a plastic binder. This mixture was allowed to solidify and was later encapsulated in a metal holder, which was pressure sealed. A variety of radionuclides were used in this operation, but the only one having a half-life greater than 60 days was cobalt-60 (^{60}Co). Licensed activities were terminated as of May 1993, and stock materials containing residual radioactive material were disposed of according to authorized procedures. Decontamination activities included the initial identification and removal of affected equipment. The site was then surveyed to demonstrate that the radiological conditions satisfy regulatory agency criteria for release.

A.2.1 Identify the Radionuclides of Concern

(**Section 4.5.1**)

More than 15 half-lives have passed for the materials with a half-life of 60 days or less. Based on radioactive decay and the initial quantities of the radionuclides, the quantities that could remain at the site are negligible. A characterization survey confirmed that no residual radionuclides, other than ^{60}Co, were present.

[1] The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

A.2.2 Determine Derived Concentration Guideline Levels for Residual Radioactive Material

(**Section 4.5**)

The objective of this survey is to demonstrate that residual radioactive material in excess of the release criteria is not present at the site using derived concentration guideline levels (DCGLs). The DCGL for average concentrations over a wide area ($DCGL_W$) for ^{60}Co used for evaluating survey results is 8,300 becquerels (Bq) per square meter (m^2) (5,000 disintegrations per minute [dpm]/100 square centimeters [cm^2]) for surface residual radioactive material on structures. The $DCGL_W$ for residual radioactive material in soil is 140 Bq per kilogram (kg) (3.8 picocuries [pCi] per gram [g]).[2]

A.2.3 Classify Areas Based on Residual Radioactive Material Potential

(**Section 4.6.1**)

This facility consists of one administration/manufacturing building situated on approximately 0.4 hectare (1.0 acre) of land as shown in **Figure A-1**. The building is a concrete block structure on a poured concrete slab with a poured concrete ceiling. The northern portion of the building housed the manufacturing operations and consists of a high-bay area of approximately 20 meters (m) x 20 m with a 7 m high ceiling. The remainder of the building is a single story with numerous small rooms partitioned by drywall construction. This portion of the building, used for administration activities, occupies an area of approximately 600 m^2 (20 m x 30 m). The license does not authorize use of radioactive materials in this area. Operating records and previous radiological surveys do not identify a potential for residual radioactive material in this section of the building. **Figure A-2** is a drawing of the building.

The property is surrounded by a chain-link security fence. At the northern end of the property, the surface is paved and was used as a parking lot for employees and for truck access to the manufacturing and shipping/receiving areas. The remainder of the property is covered with grass. There are no indications of incidents or occurrences leading to radioactive material releases from the building. Previous surveys were reviewed, and the results were determined to be appropriate for planning the FSS. These surveys identified no residual radioactive material outside the building.

[2] The DCGL values used in this appendix are meant to be illustrative examples and are not intended to be generally applied.

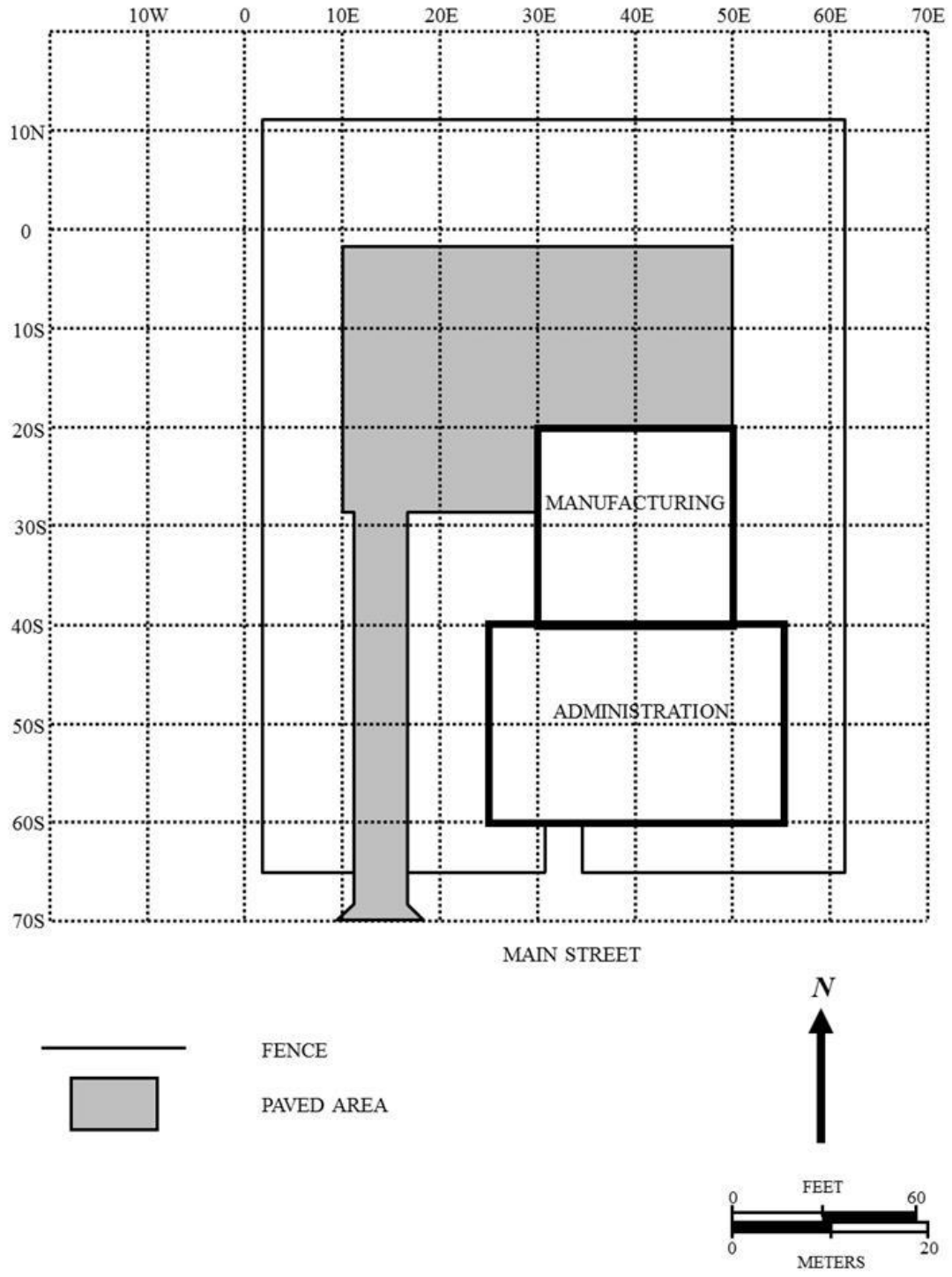

Figure A-1 Plot Plan of the Specialty Source Manufacturing Company

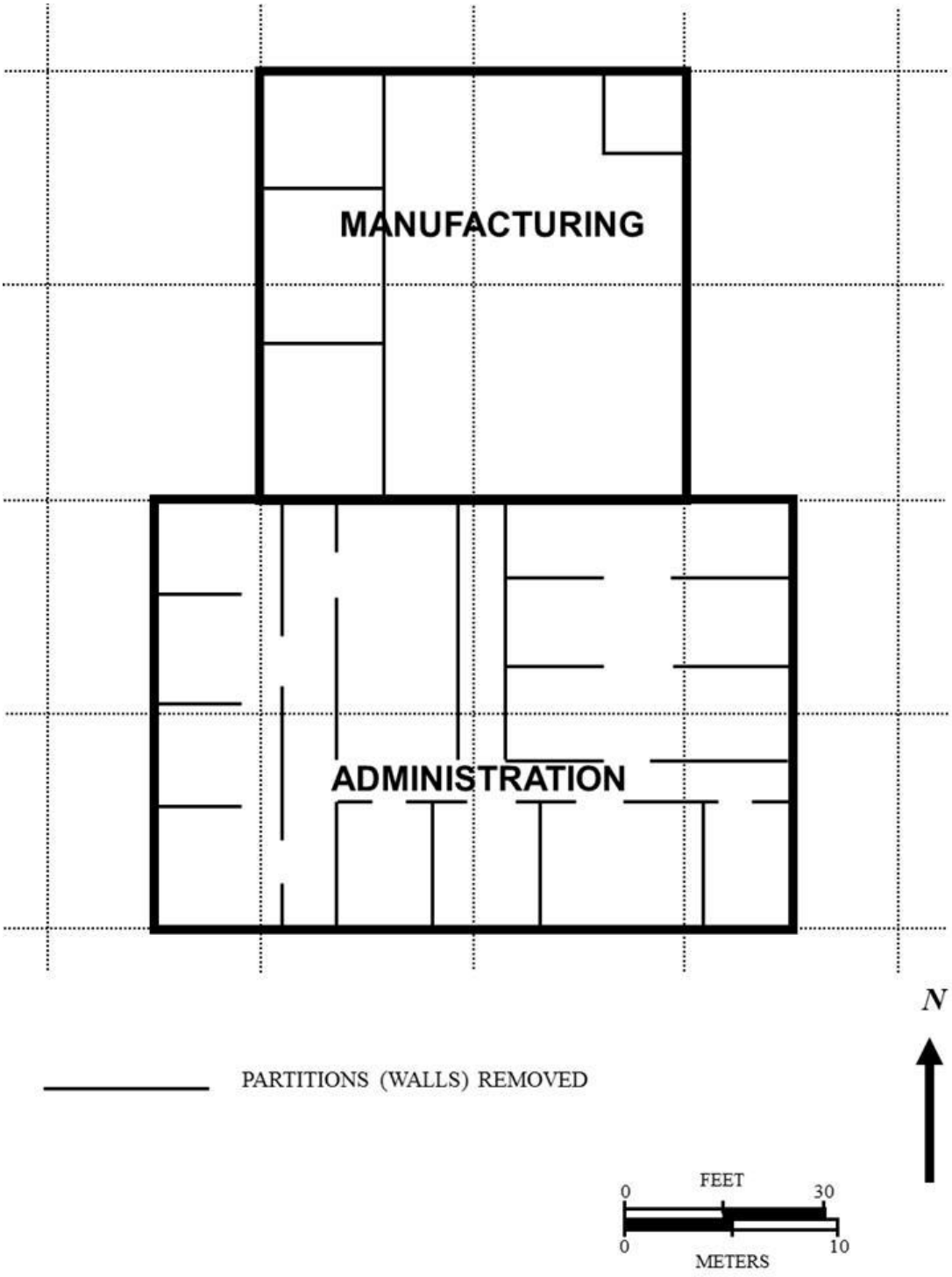

Figure A-2 Building Floor Plan

A.2.4 Identify Survey Units

(**Section 4.6.2**)

Based on the results of other surveys at the site and the site's operating history, the following survey units were used to design the FSS. All interior survey units consist of concrete surfaces (either poured concrete or cinder block) with the exception of the administration areas, which are drywall. The results of previous surveys demonstrated that the same reference area could be used to represent both the poured concrete and cinder block surfaces.

Structures

Class 1	Floor and lower walls (up to 2 m above the floor) of manufacturing area—four survey units of 140 m^2 each.
Class 2	Upper walls (over 2 m above the floor) of manufacturing area—four survey units of 100 m^2 each.
	Ceiling of manufacturing area—four survey units of 100 m^2 each.
	Paved area outside manufacturing area roll-up door—one survey unit of 60 m^2.
Class 3	Floors and lower walls of administration areas—one survey unit. Remainder of paved surfaces—one survey unit.

Land Areas

Class 3	Lawn areas—one survey unit.

While the Class 1 survey units are somewhat larger than the size of 100 m^2 recommended in **Table 4-1**, this decision to select survey units with a larger than recommended size was made by the planning team using the Data Quality Objective (DQO) process. The team decided to choose the larger size, provided that instruments used for scanning during the elevated measurement comparison had a low enough minimum detectable concentration (MDC) to meet the lower DCGL used for the elevated measurement comparison (EMC) ($DCGL_{EMC}$) expected from the larger spacing between points that would result from the decision to use larger than recommended Class 1 survey units.

A.2.5 Select Measurement Technique and Instrument Combination

(**Section 4.8**, **Chapter 6**, **Chapter 7**, and **Appendix H**)

For interior surfaces, direct measurements of gross beta activity were made using 1 minute counts on a gas flow proportional counter with an MDC of 710 Bq/m^2 (425 dpm/100 cm^2). This is less than 50 percent of the DCGL for ^{60}Co of 8,300 Bq/m^2. In addition, the calculated measurement method uncertainty for each result using the gas flow proportional counter for 1 minute direct measurements was less than the required measurement method uncertainty of 10 percent at the $DCGL_W$, or less than 830 Bq/m^2 at the $DCGL_W$ of 8,300 Bq/m^2.

Surfaces were scanned using either a 573 cm^2 floor monitor with an MDC of 6,000 Bq/m^2 (3,600 dpm/100 cm^2) or a 126 cm^2 gas flow proportional counter with an MDC of 3,300 Bq/m^2 (2,000 dpm/100 cm^2). The calculated measurement method uncertainty for each measurement

using the floor monitor and the gas flow proportional counter with a scan speed of 0.5 m per second (s) was less than the required measurement method uncertainty of 33 percent at the $DCGL_W$, or less than 2,800 Bq/m^2 at the $DCGL_W$ of 8,300 Bq/m^2.

Exterior surface soil samples were collected and counted in a laboratory using a germanium spectrometer with an MDC of 20 Bq/kg (0.5 pCi/g), which is less than 50 percent of the $DCGL_W$ for ^{60}Co of 140 Bq/kg. The calculated measurement method uncertainty for each measurement resulting from the sampling and laboratory process combined was less than the required measurement method uncertainty of 10 percent at the DCGL for ^{60}Co, or less than 14 Bq/kg at the $DCGL_W$ of 140 Bq/kg.

Soil surfaces were scanned using a thallium-activated sodium iodide (NaI[Tl]) scintillator with an MDC of 185 Bq/kg (5.0 pCi/g) of ^{60}Co. The calculated measurement method uncertainty for each measurement collected using the NaI(Tl) scintillator with a scan speed of 0.5 m/s was less than the required measurement method uncertainty of 33 percent at the $DCGL_W$, or less than 47 Bq/kg at the $DCGL_W$ of 140 Bq/kg.

Figure A-3 shows examples of scanning patterns used in each of the Class 1, 2, and 3 areas.

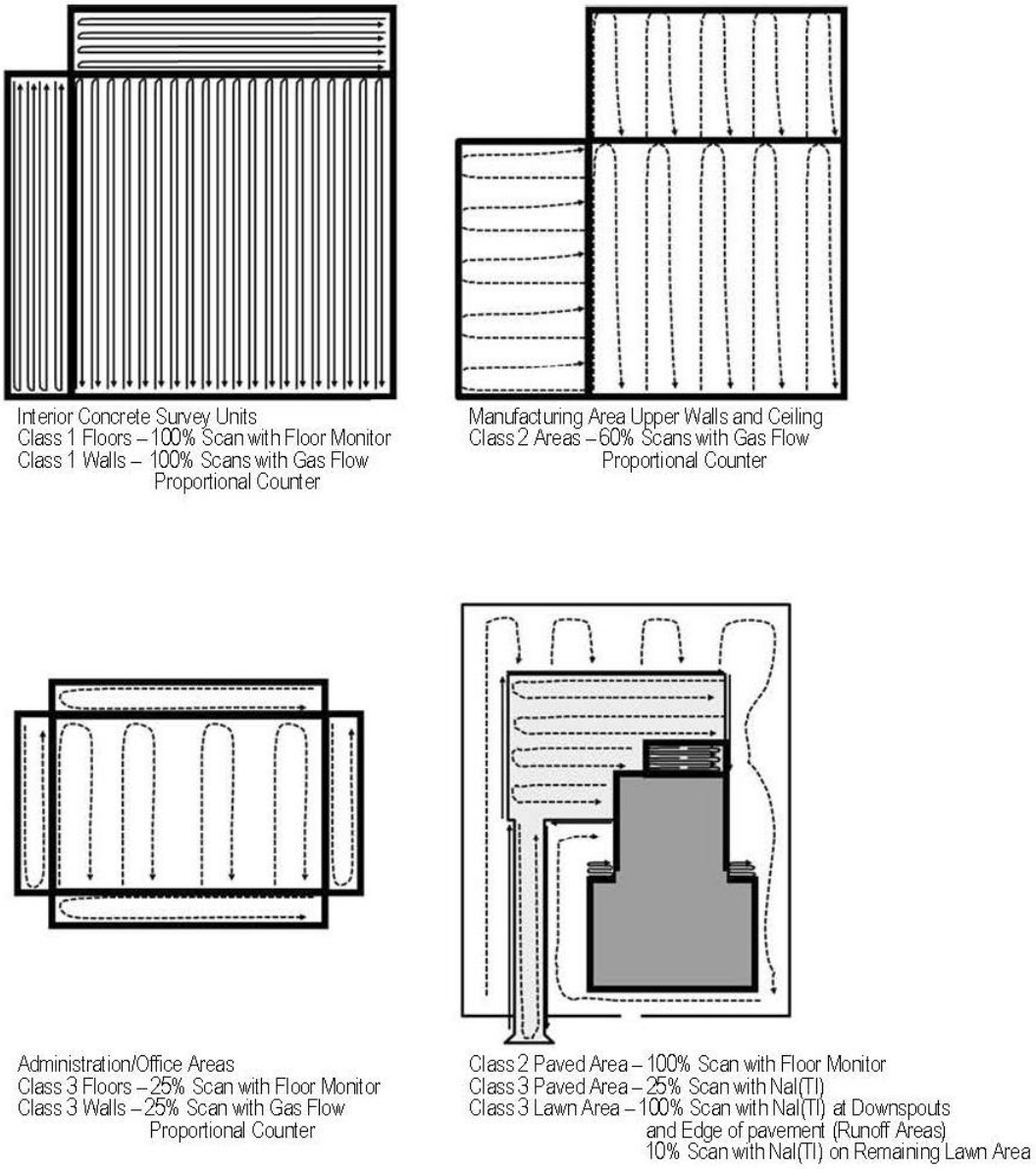

Figure A-3 Examples of Scanning Patterns for Each Survey Unit Classification

A.2.6 Select Representative Reference (Background) Areas

(**Section 4.6.3**)

For the purposes of evaluating gross beta activity on structure surfaces, a building of similar construction was identified on the property immediately east of the site. This building served as a reference for surface activity measurements. Two reference areas—one for concrete surfaces and one for drywall surfaces—were required. Because ^{60}Co is not a constituent of background and evaluation of the soil concentrations was radionuclide specific, a reference area was not needed for the land area surveys.

A.2.7 Prepare Area

(**Section 4.9**)

Before the survey, and as part of the site preparation process, all internal partitions were removed from the manufacturing area. Other items removed include the radioactive material control exhaust system, a liquid waste collection system, and other furnishings and fixtures not considered an integral part of the structure. Land areas were inspected for hazards, including poisonous plants, rodents, reptiles, slip and fall hazards, and so forth. Vegetation was inspected to determine the need for mowing grass or trimming other vegetation.

A.2.8 Establish Reference Coordinate Systems

(**Section 4.9.5**)

A grid was established for land areas at 10 m intervals along north-south and east-west axes in preparation for the characterization survey as shown in **Figure A-1**.

Structure surfaces were already gridded at 2 m intervals, incorporating the floors and the lower 2 m of the walls. **Figure A-4** is an example of the coordinate system installed for one of the Class 1 interior concrete survey units.

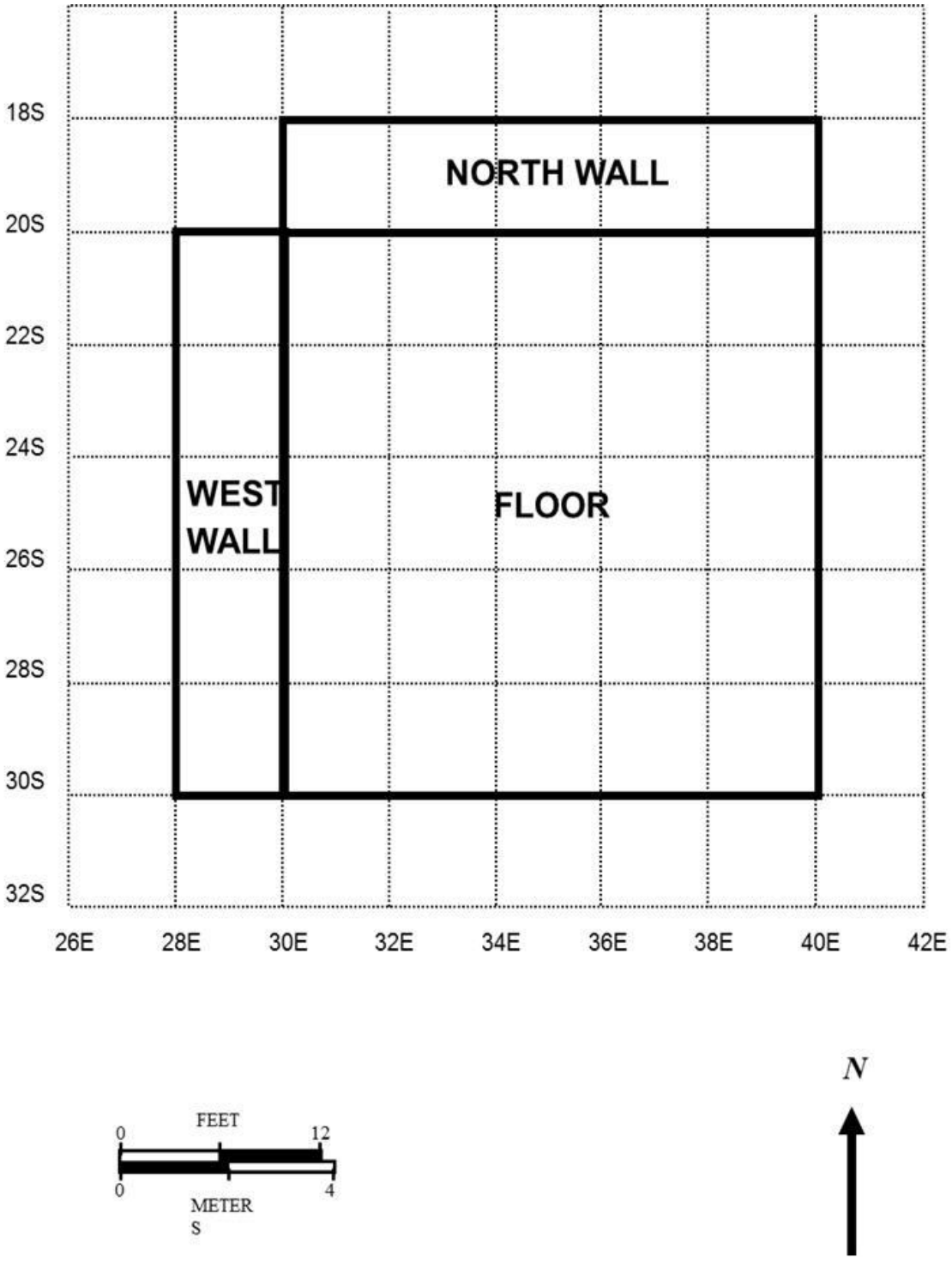

Figure A-4 Reference Coordinate System for the Class 1 Interior Concrete Survey Unit

A.3 Survey Design

A.3.1 Quantify Data Quality Objectives

(**Section 2.3**)

The null hypothesis for each survey unit is that the residual radioactive material concentrations exceed the release criteria (Scenario A). Acceptable decision error probabilities for testing the hypothesis were determined to be α = 0.05 and β = 0.05 for the Class 1 interior concrete survey units, and α = 0.025 and β = 0.05 for all other survey units.

A.3.2 Construct the Desired Power Curve

(**Section 2.5.4**, **Appendix M**)

Figure A-5 shows the desired power curve for the Class 1 interior concrete survey units. The lower bound of the gray region (LBGR) was chosen to be 4,150 Bq/m^2 (2,500 dpm/100 cm^2) as a conservative estimate of the current median value for the interior concrete survey units based on prior survey data. As a result, the gray region extends from 4,150 to 8,300 Bq/m^2 (2,500 to 5,000 dpm/100 cm^2). The survey was designed for the statistical test to have 95 percent power to decide that a survey unit containing less than 4,150 Bq/m^2 (2,500 dpm/100 cm^2) above background meets the release criteria. For the same test, a survey unit containing over 17,000 Bq/m^2 (10,000 dpm/100 cm^2) above background had less than a 2.5 percent probability of being released.

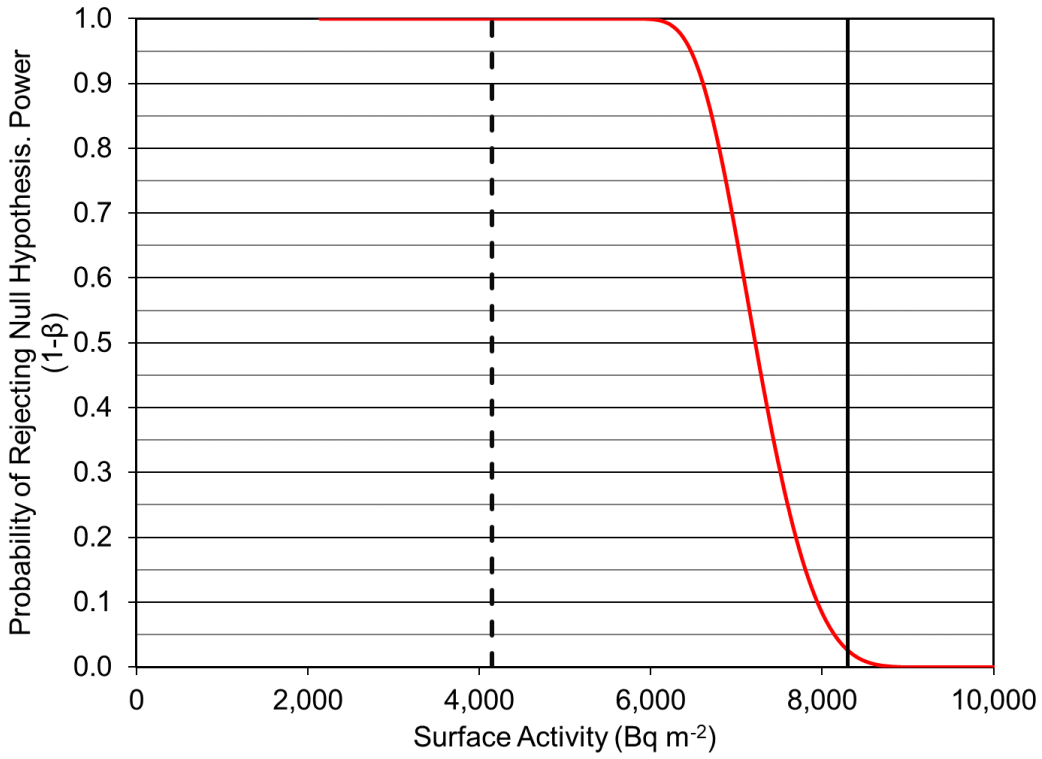

Figure A-5 Prospective Power Curve for the Class 1 Interior Concrete Survey Unit

A.3.3 Specify Sample Collection and Analysis Procedures

(**Chapter 7**)

In the Class 3 exterior survey unit, soil cores were taken to a depth of 7.5 cm (3 inches) based on development of DQOs, the conceptual site model, and the assumptions used to develop the DCGLs. Each sample was labeled with the location code and date and time of sampling, sealed in a plastic bag, and weighed before shipment to the analytical laboratory. At the laboratory, the samples were weighed, dried, and weighed again. To homogenize the samples, they were ground to a uniform particle size. A germanium detector with multichannel analyzer was used to gamma count 100 g portions.

The decision to use radionuclide-specific measurements for soil means that the survey of the Class 3 exterior soil surface survey unit was designed for use with the Sign test.

A.3.4 Provide Information on Survey Instrumentation and Techniques

(**Chapter 6**)

A gas flow proportional counter with 126 cm^2 probe area and 30 percent total efficiency (4π) response was placed on the surface at each direct measurement location, and a 1-minute count taken. Calibration and background were checked before and after each series of measurements. The net count rate corresponding to the $DCGL_W$, CR_W, is as follows:

$$CR_W = DCGLW \times A \times \varepsilon \qquad \textbf{Equation A-1}$$

where A is the probe area, and ε is the total efficiency. Substituting the values for the probe area and efficiency gives the following:

$$CR_W = (5{,}000 \text{ dpm}/100 \text{ cm}^2)(126 \text{ cm}^2)(0.30 \text{ cpm/dpm}) = 1{,}900 \text{ cpm}$$

The decision to use total activity measurements for interior surfaces meant that the survey of all the interior survey units was designed for use with the Wilcoxon Rank Sum (WRS) test for comparison with an appropriate reference area.

A.3.5 Determine Numbers of Data Points

(**Section 5.3.3**)

This facility contains 15 survey units consisting of interior concrete surfaces, interior drywall surfaces, exterior surface soil, and exterior paved surfaces.

Concrete Surfaces

The site has 12 interior concrete survey units to be compared with one reference area. The same types of instrument and method were used to perform measurements in each area.

The LBGR was selected to be 4,150 Bq/m^2 (2,500 dpm/100 cm^2), and Type I and Type II error values (α and β) of 0.05 were selected. The number of samples/measurements to be obtained, based on the requirements of the statistical tests, was determined using **Equation N-1** in **Appendix N**, reproduced here:

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{3(P_r - 0.5)^2} \qquad \textbf{Equation A-2}$$

From **Table N-2** in **Appendix N**, it is found that $Z_{1-\alpha} = Z_{1-\beta} = 1.645$ for $\alpha = \beta = 0.05$.

The parameter P_r depends on the relative shift, Δ/σ. The width of the gray region, Δ, in **Figure A-6** is 4,150 Bq/m^2 (2,500 dpm/100 cm^2), which corresponds to 950 counts per minute (cpm). Data from previous scoping and characterization surveys indicate that the background level is 283 ± 17 (1σ) cpm. The standard deviation of the contaminant in the survey unit (σ_s) is estimated at ± 235 cpm. When the estimated standard deviations in the reference area and the survey units are different, the larger value should be used to calculate the relative shift. Thus, the value of the relative shift,[3] Δ/σ, is (1,900 − 950)/235, or 4.0. From **Table N-1** in **Appendix N**, the value of P_r is approximately 1.000.

[3] Ordinarily, Δ/σ would be adjusted to a value between 1 and 3. For this example, the adjustment was not made.

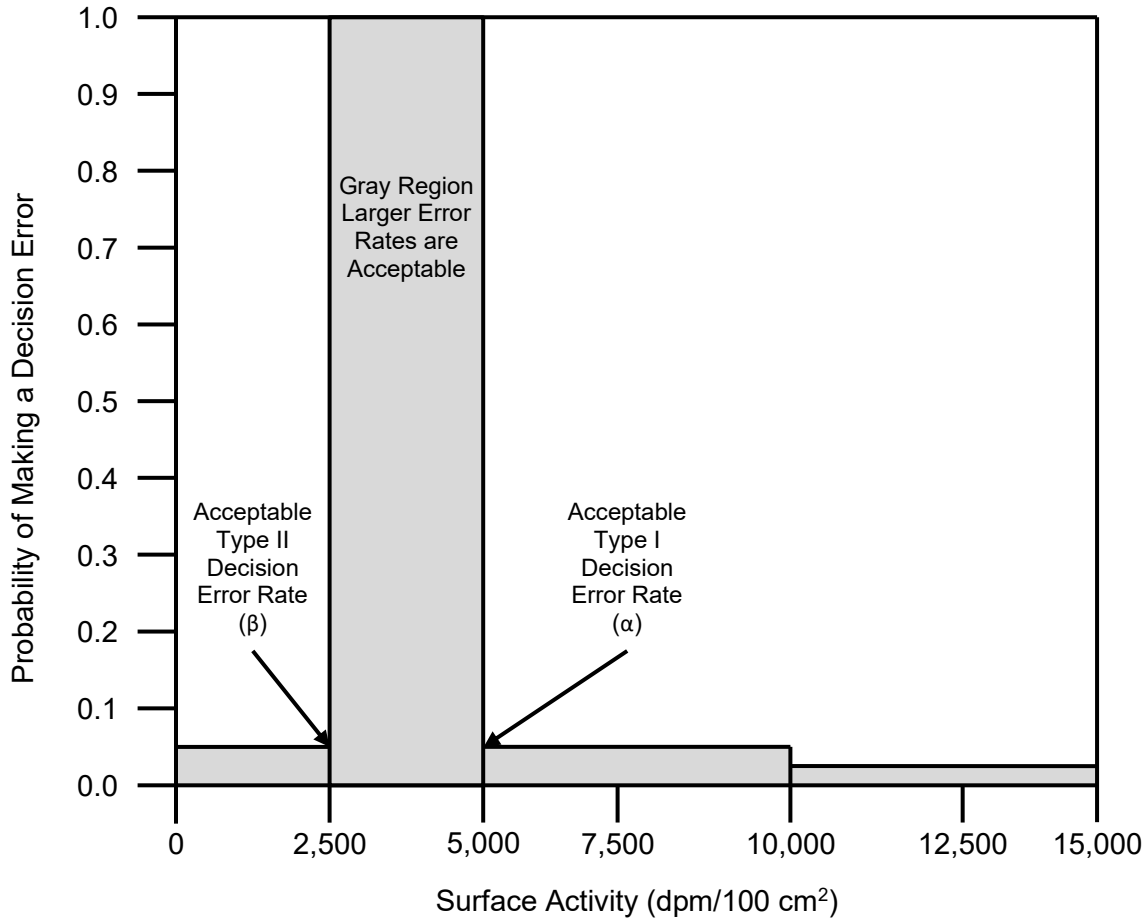

Figure A-6 Decision Performance Goal Diagram for the Class 1 Interior Concrete Survey Unit

Using Equation A-2, the number of data points for the WRS test of each combination of reference area and survey units is as follows:

$$N = \frac{(1.645 + 1.645)^2}{3(1.000 - 0.5)^2} \cong 14.4$$

Adding 20 percent and rounding up yielded 18 data points total for the reference area and each survey unit combined.[4] Of this total number, nine were planned from the reference area and nine from each survey unit. The total number of measurements calculated based on the statistical tests was 9 + (12 × 9) = 117.

[4] **Table 5-2** and **Table I-3** in **Appendix I** list *N* only for values of the relative shift up to 3.0, as *N* changes very slowly at values greater than 3.0. If using the values in **Tables 5-2** and **I-3**, the default would be to use the value for the 3.0 line, which results in *N* = 20, or 10 in the survey unit and 10 in the reference area.

A.3.6 Evaluate the Power of the Statistical Tests against the Data Quality Objectives

(**Appendix M**)

Using **Equation M-4**, the prospective power expected of the WRS test was calculated using the fact that nine samples were planned in each of the survey units and the reference area. The value of σ_s was taken to be 235 cpm, the larger of the two values anticipated for the reference area (57 cpm) and the survey unit (235 cpm). **Figure A-6** shows this prospective power curve. **Appendix M** contains additional guidance on calculating power curves.

The prospective power curve demonstrates that the survey design meets the DQOs, including the limit on Type I and Type II errors at the upper bound of the gray region and the LBGR, assuming the variance in the sample is that which was estimated. The power curve also provides an easy way to see the effect that the true concentration would have on the likelihood of rejecting the null hypothesis.

(**Section 5.3.5**)

The Class 1 concrete interior survey units each have an area of 140 m^2 (**Figure A-7**). The distance between measurement locations in these survey units is calculated using **Equation A-3,** as shown:

$$L = \sqrt{\frac{A}{0.866 \times n}} \qquad \textbf{Equation A-3}$$

$$L = \sqrt{\frac{140\ \mathrm{m}^2}{0.866 \times 9}} = 4.2\ \mathrm{m}$$

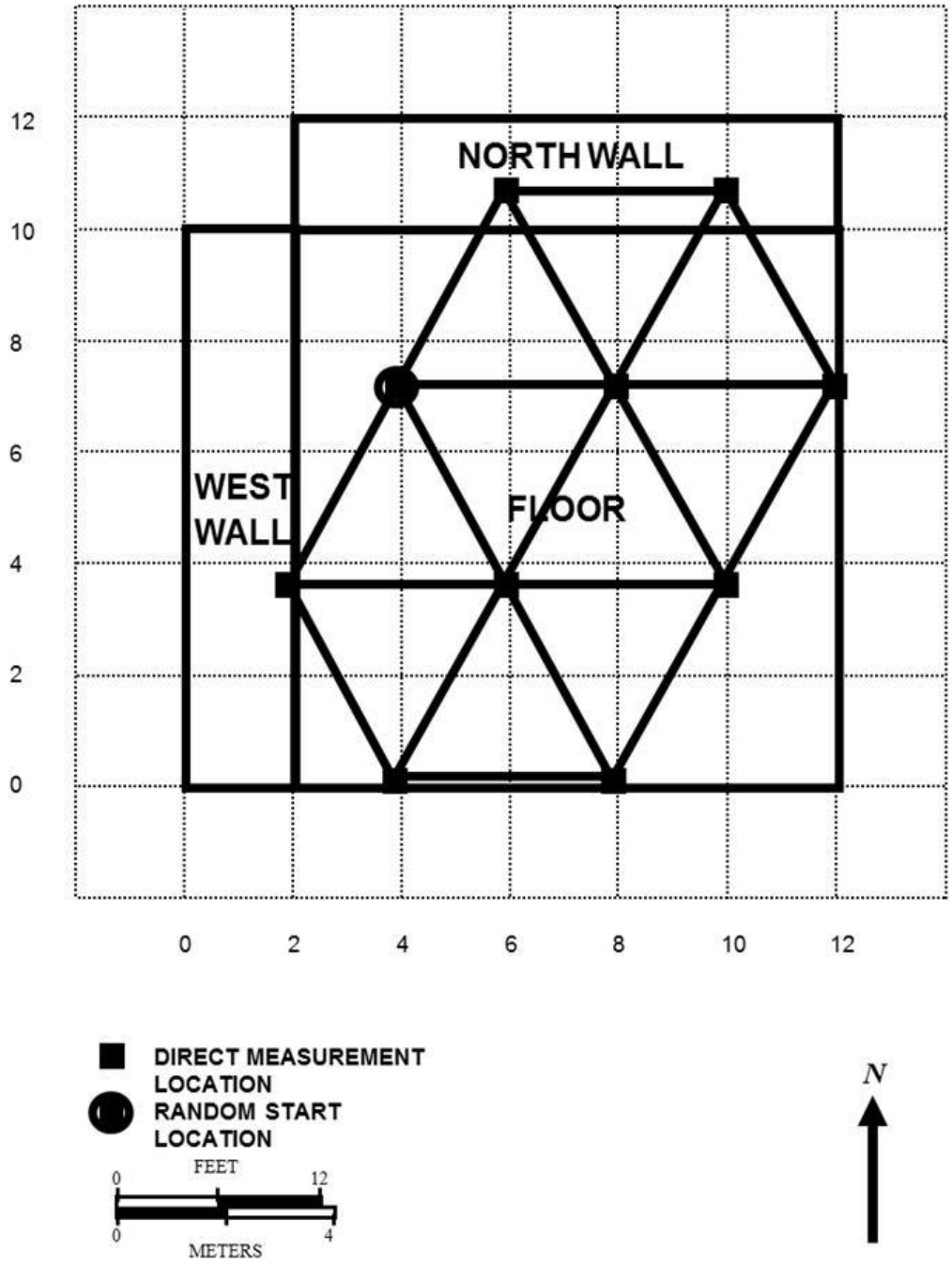

Figure A-7 Measurement Grid for the Class 1 Interior Concrete Survey Unit

A.3.7 Ensure that the Sample Size Is Sufficient for Detecting Areas of Elevated Concentrations of Radioactive Material

The result for L was rounded *down* to the nearest meter, giving $L = 4$ m. This resulted in an area between the four sampling points of $0.866L^2 = 13.9$ m^2. The scanning MDC of 6,000 Bq/m^2 (3,600 dpm/100 cm^2) of the least sensitive of the two scanning instruments (the

floor monitor) was well below the $DCGL_W$ of 8,300 Bq/m^2 (5,000 dpm/100 cm^2). Therefore, no adjustment to the number of data points was needed to account for areas of elevated activity.

A.3.8 Specify Sampling Locations

(Section 5.3.7)

Two random numbers between 0 and 1 were generated to locate the random start for the sampling grid. Using **Table I-13** in **Appendix I**, an unbiased third party selected 0.322467 and 0.601951. The random start for the triangular sampling pattern was found by multiplying these numbers by the length of the reference grid X and Y axes:

$$X = 0.322467 \times 12 \text{ m} = 3.9 \text{ m}$$

$$Y = 0.601951 \times 12 \text{ m} = 7.2 \text{ m}$$

The first row of measurement locations was laid out at 4 m intervals parallel to the x-axis of the reference grid. The second row was positioned (0.866 × 4) = 3.5 m from the first row, with measurement locations offset by 2 m from those in the first row. **Figure A-7** shows the measurement grid. When the measurement grid was constructed, 10 measurement locations were identified within the boundaries of the survey unit, which is greater than the 9 measurement locations calculated to be required for the statistical test. Because the spacing between the measurements (L) is important for identifying areas of elevated activity, all 10 of the identified sampling locations were used.

A.3.9 Develop Quality Control Procedures

(Section 4.2.2)

Quality control (QC) procedures were developed for performing QC checks on all instruments, and for verifying and validating data.

A.3.10 Document Results of Planning in a Quality Assurance Project Plan

(Appendix D)

A Quality Assurance Project Plan (QAPP) was developed to identify all applicable quality assurance requirements.

A.4 Conducting Surveys

A.4.1 Perform Reference (Background) Area and Survey Unit Measurements and Scanning

(Chapter 6)

Measurements were made in both the survey units and reference areas using the gas flow proportional counter described in **Section A.3.4**. Measurements were made using standard operating procedures and documented on standard data collection forms.

A.4.2 Collect and Analyze Soil Samples

(Chapter 7)

Soil samples were collected and sent to an independent laboratory for analysis.

A.5 Evaluating Survey Results

A.5.1 Perform Data Quality Assessment

(Section 8.2)

Table A-1 gives the data from one Class 1 interior concrete survey unit and the associated reference area. Because 10 sampling locations were identified, 10 results are listed for the survey unit.[5] The average[6] measurement in the survey unit is 2,433 cpm, and, in the reference area, the average is 287 cpm. The means and the medians are nearly equal in both cases. The standard deviations are also consistent with those estimated during the survey design. The survey unit clearly contains residual radioactive material close to the $DCGL_W$ of 1,900 cpm (calculated using **Equation A-1**).

The stem and leaf displays (refer to **Appendix L, Section L.1**) for the data appear in **Figure A-8**. They indicate that the data distributions are unimodal with no notable asymmetry. There are two noticeably extreme values in the survey unit dataset, at 1,784 and 2,584 cpm. These are both about two standard deviations from the mean. A check of the data logs indicated nothing unusual about these points, so there was no reason to conclude that these values were due to anything other than random measurement variability.

A quantile-quantile plot of these data, shown in **Figure A-9**, is consistent with these conclusions. **Section L.2** of **Appendix L** includes instructions for making quantile-quantile plots. The median and spread of the survey unit data are clearly above those from the reference area. The middle part of the curve has no sharp rises. However, the lower and upper portions of the curve both show a steep rise due to the two extreme measurements in the survey unit dataset.

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5 There are also 10 results listed for the reference area. This is only because there were also 10 locations identified there when the grid was laid out. Had nine locations been found, the survey would proceed using those nine locations. There is no requirement that the number of sampling locations in the survey unit and reference area be equal. It is only necessary that at least the minimum number of samples required for the statistical tests is obtained in each.

6 In MARSSIM, “average” and “mean” both refer to the arithmetic mean.

Table A-1 Class 1 Interior Concrete Survey Unit and Reference Area Data

Data Type	Reference Area (cpm)	Survey Unit (cpm)
Sample 1	284	2,174
Sample 2	227	2,197
Sample 3	202	2,150
Sample 4	359	2,067
Sample 5	290	2,244
Sample 6	378	2,209
Sample 7	246	1,784
Sample 8	284	2,303
Sample 9	334	2,504
Sample 10	265	2,221
Sample Mean	287	2,185
Sample Standard Deviation	56	182
Sample Median	284	2,203

Reference Area				
200	02	27	46	
250	65	84	84	90
300	34			
350	59	78		

Survey Unit			
1700	84		
1800			
1900			
2000	67		
2100	50	74	97
2200	09	21	44
2300	03		
2400			
2500	04		

Figure A-8 Stem and Leaf Displays for Class 1 Interior Concrete Survey Units

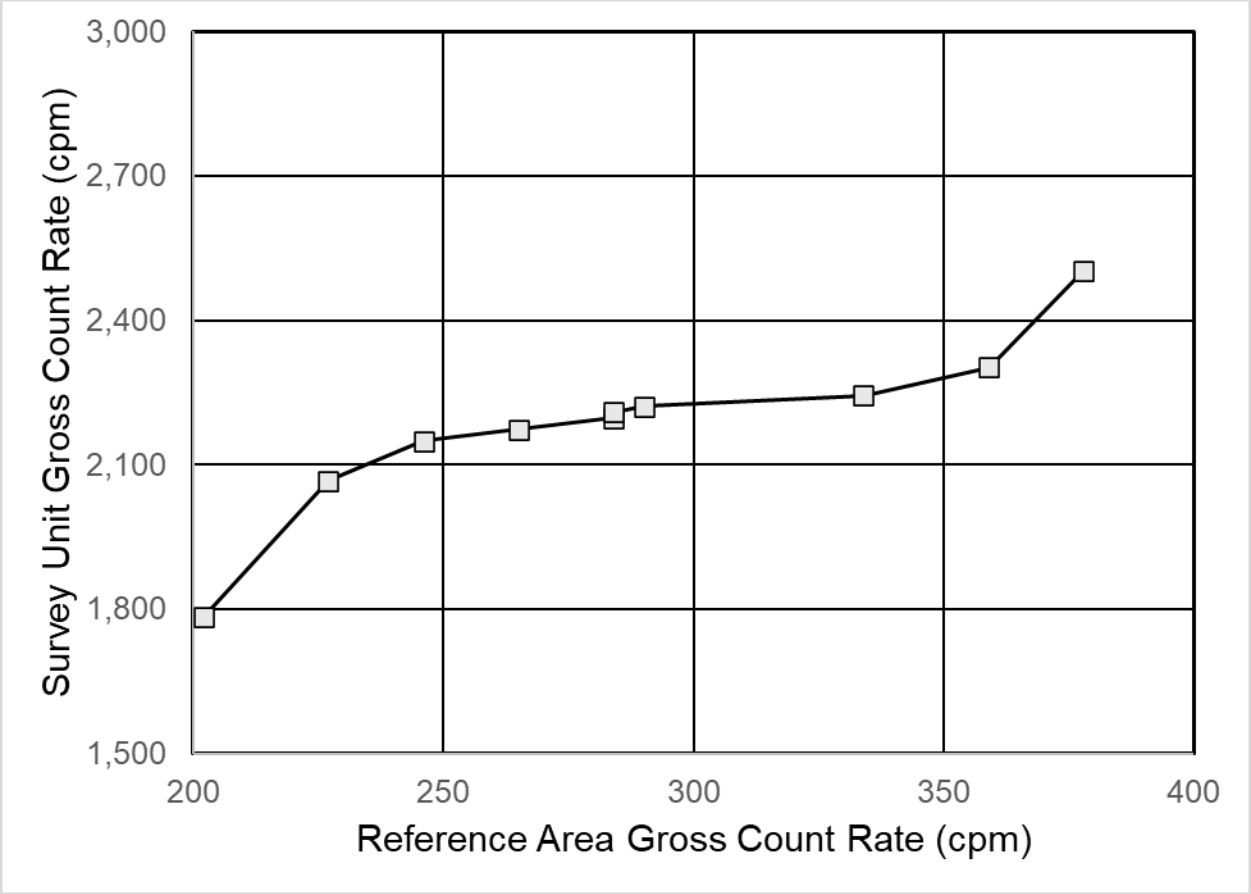

Figure A-9 Quantile-Quantile Plot for the Class 1 Interior Concrete Survey Unit

A.5.2 Conduct Elevated Measurement Comparison

(Section 8.6.1)

The $DCGL_W$ is 1,900 cpm above background. Based on an area between measurement locations of 13.9 m^2 for L = 4 m, the $DCGL_{EMC}$ is 2,700 cpm above background. Even without subtracting the average background value of 287 cpm, no survey unit measurements exceeded this value. All survey unit measurements exceeded the $DCGL_W$, and six exceeded 2,187 cpm—the $DCGL_W$ plus the average background. If any of these data exceeded three standard deviations of the survey unit mean, they might have been considered unusual, but this was not the case. Thus, while the amount of residual radioactive material appeared to be near the release criterion, there was no evidence of smaller areas with elevated concentrations of residual radioactive material.

A.5.3 Conduct Statistical Tests

(Section 8.4)

For the Class 1 interior concrete survey unit, the WRS statistical test was appropriate because, although the radionuclide of concern does not appear in background, radionuclide-specific measurements were not made. This survey unit was classified as Class 1, so the 10 measurements performed in the reference area and the 10 measurements performed in the survey unit were made on random start triangular grids.

Table A-2 shows the results of the 20 measurements in the first column. The average and standard deviation of the reference area measurements were 287 and 56, respectively. The average and standard deviation of the survey unit measurements were 2,185 and 182, respectively.

The analysis proceeded as described in **Section 8.4**. In the (Area) column, the code "R" is inserted to denote a reference area measurement and "S" to denote a survey unit measurement. In the (Data) column, the data were simply recorded as the measured count rates. The values in the (Adjusted Data) column were obtained by adding the $DCGL_W$ (1,900 cpm) to the reference area measurements and leaving the survey unit measurements unchanged. The ranks of the adjusted data appear in the (Ranks) column. They range from 1 to 20 because there is a total of 20 (10 + 10) measurements. The sum of all the ranks[7] is 20(20 + 1)/2 = 210. It is recommended to check this value as a guard against errors in the rankings.

The (Reference Area Ranks) column contains only the ranks belonging to the reference area measurements. The total is 99. This was compared with the entry in **Table I-6** for $\alpha = 0.05$, with $n = 10$ and $m = 10$. This critical value is 127. Thus, the sum of the reference area ranks was *less* than the critical value, and the null hypothesis—that the survey unit concentrations exceed the $DCGL_W$—was not rejected.

The retrospective power curve for the WRS test was constructed as described in **Appendix M**, using **Equations M-1, M-2,** and **M-3**, together with the actual number of concentration measurements obtained, N. The power as a function of Δ/s was calculated using the observed standard deviation, $s = 15.4$, in place of σ. The values of Δ/σ were converted to a corresponding count rate, CR, in cpm using **Equation A-4:**

$$CR = CR_W - \left(\Delta/\sigma\right) s \qquad \textbf{Equation A-4}$$

where CR_W is the count rate corresponding to the $DCGL_W$.

The results for this example are plotted in **Figure A-10**, showing the probability that the survey unit would have passed the release criterion using the WRS test versus the true mean of the count rate of residual radioactive material in the survey unit. This curve shows that the DQOs were easily met. The curve shows that a survey unit with less than about 130 cpm above background would almost always pass and that a survey unit with more than about 170 cpm above background would almost always fail. This supports the conclusion that the Class 1 interior survey unit failed not because the statistical test lacked sufficient power to reject the null

[7] If n is the number of measurements in the survey unit and m is the number of measurements in the reference area, the sum of the ranks of the combined datasets is $(n+m)*(n+m+1)$.

hypothesis, but because the concentration of residual radioactive material in the survey unit is above the $DCGL_W$.

Table A-2 WRS Test for Class 1 Interior Concrete Survey Unit

Data	Area	Adjusted Data	Ranks	Reference Area Ranks
284	R	2,184	9.5	9.5
227	R	2,127	4	4
202	R	2,102	3	3
359	R	2,259	17	17
290	R	2,190	11	11
378	R	2,278	18	18
246	R	2,146	5	5
284	R	2,184	9.5	9.5
334	R	2,234	15	15
265	R	2,165	7	7
2,174	S	2,174	8	0
2,197	S	2,197	12	0
2,150	S	2,150	6	0
2,067	S	2,067	2	0
2,244	S	2,244	16	0
2,209	S	2,209	13	0
1,784	S	1,784	1	0
2,303	S	2,303	19	0
2,504	S	2,504	20	0
2,221	S	2,221	14	0
Sum:			210	99

A.5.4 Estimate Amount of Residual Radioactivity

The amount of residual radioactive material in the survey unit above background was estimated following the WRS test using the difference between the mean measurement in the survey unit and the mean measurement in the reference area: $\delta = 2{,}185 \text{ cpm} - 287 \text{ cpm} = 1{,}898 \text{ cpm}$. This was converted to a surface area activity concentration of 8,400 Bq/m^2 (5,000 dpm/100 cm^2), which slightly exceeds the $DCGL_W$.

The difference in the median measurements (2,203 cpm – 284 cpm = 1,919 cpm) was converted to a surface activity concentration of 8,500 Bq/m^2 (5,100 dpm/100 cm^2). This is slightly higher than the mean and also slightly exceeds the $DCGL_W$.

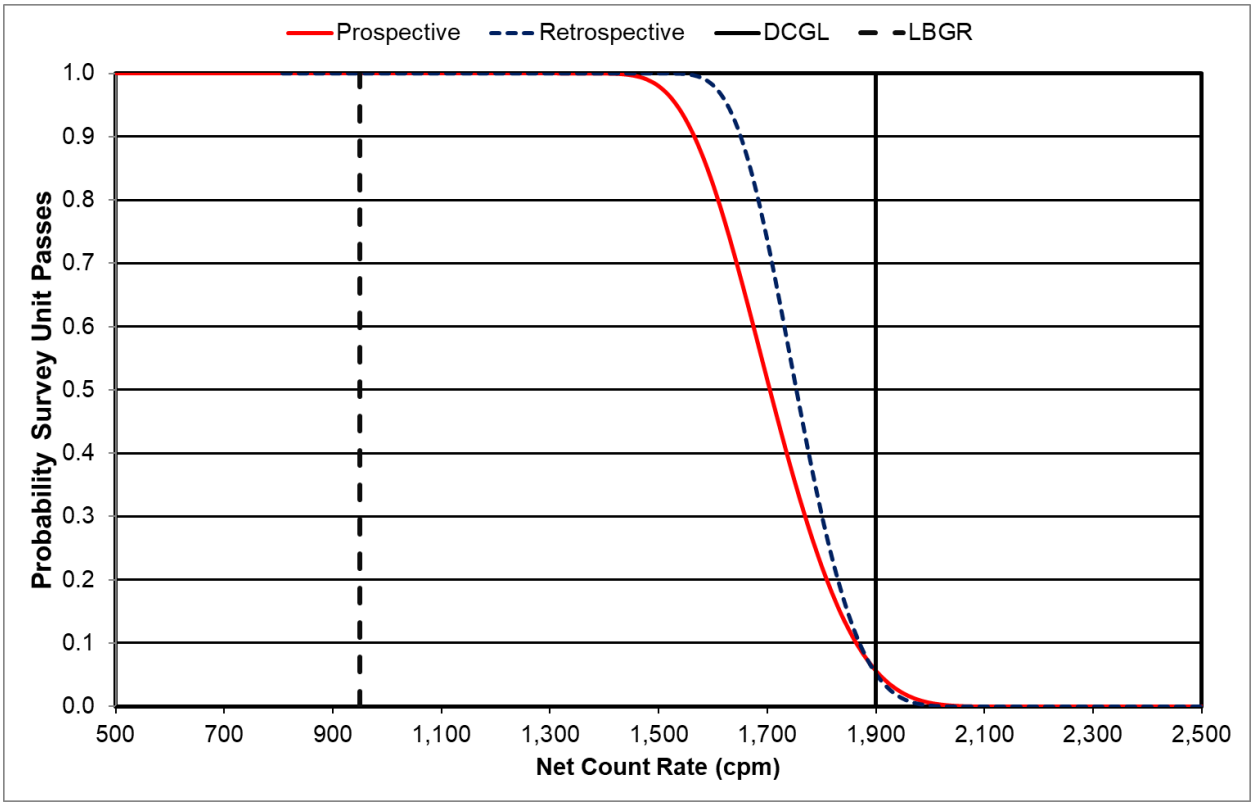

Figure A-10 Retrospective and Prospective Power Curves for the Class 1 Interior Concrete Survey Unit

APPENDIX B
SIMPLIFIED PROCEDURE FOR CERTAIN USERS OF SEALED SOURCES, SHORT HALF-LIFE MATERIALS, AND SMALL QUANTITIES

Many users of radioactive materials may employ a simplified procedure to demonstrate regulatory compliance for unrestricted release, avoiding complex final status surveys (FSSs). Sites that qualify for simplified decommissioning procedures are those where radioactive materials have been used or stored only in the form of nonleaking, sealed sources; short half-life radioactive materials (e.g., $t_{1/2} \leq 120$ days)[1] that have since decayed to insignificant quantities; small quantities exempted or not requiring a specific license from a regulatory authority; or combinations of the above.

The user of a site that may qualify for implementation of a simplified procedure should[2] provide the regulatory authority with at least both of the following:

- a certification that no residual radioactive material attributable to the user's activities is detectable by generally accepted survey methods for FSSs
- documentation on the disposal of radioactive materials, such as the information required in U.S. Nuclear Regulatory Commission Form 314, "Certificate of Disposition of Materials"

The regulatory authority may use this minimum information to document protection of both public health and safety and the environment, based on the transfer, decay, or disposal of radioactive material in some authorized manner.

Normally, the absence of residual radioactive material can be demonstrated by (1) documenting the amounts, kinds, and uses of radionuclides as well as the processes involved, (2) conducting a radiation survey of the site, and (3) submitting a report on this survey. More specifically, a user of a qualified site should document from process knowledge and the nature of the use that either no or unmeasurable quantities of radioactive material remain on site—whether on surfaces, buried, embedded, submersed, or dissolved. The submittal to the regulatory authority should include possession history, use of the radioactive materials, and, if applicable, results of all leak tests. Where only small quantities or short half-life materials were handled, the regulatory authority may consider the documentation on a case-by-case basis.

For those sites where a simple FSS is conducted to demonstrate compliance with the release criteria, the FSS report should include the following information:

- basis for selecting the instrumentation used for the survey
- nature of the radionuclides surveyed

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[1] Many nuclear medicine facilities will fall into this category; however, for those facilities handling long-lived radionuclides, this appendix may not be applicable.

[2] The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

- measurement techniques and instruments used, including references for procedures and protocols used to perform the measurements
- minimum detectable concentrations and required uncertainties of the measurement methods used to perform the measurements
- calibration, field testing, and maintenance of the instrumentation
- qualifications of the personnel using the instrumentation
- methods used to interpret the survey measurements
- qualifications of the personnel interpreting the survey measurements
- measurement results and measurement locations, including the operator's name, instrument model and serial number, date the measurement was performed, and traceability of the measurement location

The number of measurements in each survey unit and each reference area can be determined using **Table 5-2** for sites where the radionuclide of concern is present in background. The number of measurements for each survey unit where the radionuclide is not present in background can be determined using **Table 5-3.** Values for acceptable Type I and Type II decision error levels (α and β) and the relative shift (Δ/σ) can be determined as described in **Section 5.3.** For sites where the simplified approach in this appendix is appropriate, reasonably conservative values for these parameters would be $\alpha = 0.05$, $\beta = 0.05$, and $\Delta/\sigma = 1$. After increasing the number of measurements by 20 percent to ensure adequate power for the statistical tests, **Table 5-2** and **Table 5-3** list a value of approximately 30 measurements for each survey unit and each reference. Therefore, 30 measurements may be used in place of the guidance in **Section 5.3** at sites that qualify for the simplified survey design process.

The results of the survey should be compared to derived concentration guideline levels (DCGLs) using an appropriate statistical test, such as the Sign test or Wilcoxon Rank Sum test. However, if all measurements are less than the DCGL for average concentrations over a wide area ($DCGL_W$), then the statistics do not need to be addressed because the conclusions are obvious. Similarly, if the mean[3] of the measurements exceeds the $DCGL_W$, the survey unit obviously fails to demonstrate compliance, and the statistics do not need to be addressed.

Radiation levels and concentrations should be reported using the following units:

- for external absorbed dose rates
  - milligrays (microrads) per hour at 1 meter (m) from surfaces
- for levels of radioactive materials, including alpha and beta measurements
  - becquerels (Bq)/m^2 (disintegrations per minute [dpm]/100 square centimeters [cm^2], picocuries [pCi]/100 cm^2) (removable and/or fixed) for surfaces

[3] In MARSSIM, "average" and "mean" both refer to the arithmetic mean.

- Bq/liter (L) (pCi/milliliter [mL] or pCi/L) for water
- Bq/kilogram (kg) (pCi/gram [g]) for solids such as soils or concrete

APPENDIX C
REGULATIONS AND REQUIREMENTS ASSOCIATED WITH RADIATION SURVEYS AND SITE INVESTIGATIONS[1]

C.1 Statutory Authorities of the U.S. Environmental Protection Agency

The U.S. Environmental Protection Agency (EPA) administers several statutes that address various aspects of the cleanup of sites affected by residual radioactive material. Listed below are the statutes, the implementing regulations, and the responsible EPA offices.

C.1.1 The Office of Air and Radiation

The Office of Air and Radiation administers several statutes and implementing regulations:

- Clean Air Act as amended in 1990 (CAA), 42 United States Code (U.S.C.) §§ 7401–7671: The CAA protects and enhances the Nation's air quality through national ambient air quality standards, new source performance standards, and other provisions. Radionuclides are a hazardous air pollutant regulated under Section 112 of the CAA.
  - Title 40 of the *U.S. Code of Federal Regulations* (CFR) Part 61, "National Emission Standards for Hazardous Air Pollutants," for radionuclides
- Atomic Energy Act of 1954, as amended (AEA), 42 U.S.C. §§ 2011–2296: The AEA requires the management, processing, and use of radioactive materials in a manner that protects public health and the environment. The EPA, U.S. Nuclear Regulatory Commission (NRC), and U.S. Department of Energy (DOE) are assigned specific sections and authorities under the AEA. In some cases, the AEA mission and authorities are shared across agencies. AEA-defined source, special nuclear, and byproduct materials must be managed, processed, and used in a manner that protects public health and the environment. Under the AEA and Reorganization Plan No. 3 of 1970, the EPA is authorized to issue Federal guidance on radiation protection matters as deemed necessary by the Agency or as mandated by Congress. This guidance may be issued as regulations, given that the EPA has the authority to promulgate generally applicable radiation protection standards under Reorganization Plan No. 3. For example, under AEA authority, the EPA promulgated its environmental radiation protection standards for nuclear power operations in 40 CFR Part 190, "Environmental Radiation Protection Standards for Nuclear Power Operations."
  - 40 CFR Part 191, "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes"
- Uranium Mill Tailings Radiation Control Act of 1978, as amended (UMTRCA), 42 U.S.C. § 2022: UMTRCA requires stabilization and control of byproduct materials (primarily mill tailings) at licensed commercial uranium and thorium processing sites. The

[1] The user of the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) should consult the text of the statutes and regulations listed in this appendix to ensure compliance with all requirements applicable to a specific site and to ensure the use of current versions of applicable statutes and regulations.

NRC and the DOE implement standards under UMTRCA. The implementing regulations provide design requirements for closure of the mill's waste disposal area and establish technical criteria related to the operation, decontamination, decommissioning, and reclamation of uranium or thorium mills and mill tailings.

  – 40 CFR Part 192, "Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings"

- Nuclear Waste Policy Act of 1982, as amended (NWPA), 42 U.S.C. § 10101: The NWPA is intended to provide an orderly scheme for the selection and development of repositories for high-level radioactive waste and spent nuclear fuel.

- Indoor Radon Abatement Act of 1988, 15 U.S.C. § 2601, §§ 301–311: This law continued incentives for States to establish radon programs, conduct surveys, and develop information on the public health hazard of radon. It also required all Federal agencies to conduct studies of radon contamination in federally owned buildings in high radon risk areas.

C.1.2 The Office of Land and Emergency Management

The Office of Land and Emergency Management (formerly known as the Office of Solid Waste and Emergency Response) administers several statutes and regulations:

- Resource Conservation and Recovery Act of 1976 (RCRA), 42 U.S.C. §§ 6901–6992k: RCRA provides for detailed regulation of hazardous waste from generation to final disposal. Hazardous waste generators and transporters must comply with EPA standards. Owners and operators of treatment, storage, or disposal facilities must obtain RCRA permits. Materials defined in the AEA are expressly excluded from the definition of solid waste and thus from regulation under RCRA. Naturally occurring radioactive materials and mixed wastes (RCRA waste and AEA materials comingled), however, are not excluded.

- Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended (CERCLA), 42 U.S.C. §§ 9601–9675: CERCLA, commonly known as Superfund, authorizes the EPA, consistent with 40 CFR Part 300, "National Oil and Hazardous Substances Pollution Contingency Plan," to provide for remedial action in response to releases or substantial threats of releases of hazardous substances into the environment. A hazardous substance is defined as any substance designated or listed under the CAA, the Federal Water Pollution Control Act Amendments of 1972 (Clean Water Act, as amended) (42 U.S.C. §§ 7401–7671), the Toxic Substances Control Act of 1976 (TSCA) (15 U.S.C. §§ 2601–2692), and RCRA. Because the CAA designated radionuclides as a hazardous air pollutant, the provisions of CERCLA apply to radionuclides.

C.1.3 The Office of Water

The Office of Water administers several statutes and implementing regulations:

- Safe Drinking Water Act of 1974, as amended (SDWA), 42 U.S.C. §§ 300f–300j-26: The SDWA seeks to protect public water supply systems through protection of groundwater. Any radioactive substance that may be found in water is regulated under the SDWA.

  - 40 CFR 141.66, “Maximum contaminant levels for radionuclides”

- Clean Water Act of 1972, as amended, 33 U.S.C. §§ 1251–1387: The Clean Water Act includes State water quality standards and Federal pretreatment standards for discharge into a publicly owned treatment works.

C.1.4 The Office of Chemical Safety and Pollution Prevention

The Office of Chemical Safety and Pollution Prevention administers TSCA:

- Toxic Substances Control Act of 1976 (TSCA), 15 U.S.C. §§ 2601–2692: TSCA regulates the manufacture, distribution in commerce, processing, use, and disposal of chemical substances and mixtures. Materials defined in the AEA are expressly excluded from TSCA; however, naturally occurring radionuclides are not excluded.

C.2 U.S. Department of Energy Regulations and Requirements

C.2.1 DOE Authorities

The Department of Energy Organization Act of 1977, which created the DOE; the Energy Reorganization Act of 1974, as amended (42 U.S.C. § 5801 et seq.), which created the Energy Research and Development Administration (ERDA); and the AEA provide the basic authorities of the DOE. **Table C-1** shows the principal DOE statutory authorities and requirements that pertain to radiation protection, some of which are described in this section. DOE orders are enforceable on DOE contractors as a contractual provision when the orders are included in DOE contracts.

C.2.1.1 Atomic Energy Act of 1954, as amended

The AEA established a program of private ownership and use of nuclear materials and nuclear facilities, such as nuclear research reactors, and a program for Government regulation of those applications. (Before 1954, all source, byproduct, and special nuclear materials were Government owned.) The Atomic Energy Commission (AEC)[2] was given both the regulatory authorities and the mission to develop both the peaceful and military uses of atomic energy. The AEA also retained the AEC as the civilian agency responsible for weapons programs production, development, and research consistent with the Atomic Energy Act of 1946.

Under the AEA, the AEC was responsible for developing regulations ensuring the safety of commercial facilities and establishing requirements that ensure public protection from radiation and radioactive materials resulting from or used in its research, development, and production activities.

[2] The AEC was created by the Atomic Energy Act of 1946, not the 1954 act.

Table C-1 DOE Authorities, Orders, and Regulations Related to Radiation Protection

Statutes
Atomic Energy Act of 1954, as amended
Energy Reorganization Act of 1974
Department of Energy Organization Act of 1977
Uranium Mill Tailings Radiation Control Act of 1978, as amended
Nuclear Non-Proliferation Act of 1978
West Valley Demonstration Project Act of 1980
Low-Level Radioactive Waste Policy Act of 1980
Nuclear Waste Policy Act of 1982
Low-Level Radioactive Waste Policy Amendments Act of 1985
Price-Anderson Amendments Act of 1988
Energy Policy Act of 1992
Waste Isolation Pilot Plant Land Withdrawal Act of 1992
DOE Regulations
10 CFR Part 830, "Nuclear Safety Management"
10 CFR Part 835, "Occupational Radiation Protection"
10 CFR Part 851, "Worker Safety and Health Program"
Executive Orders
Executive Order 12580, "Superfund Implementation"

DOE Orders
DOE Order 231.1B, "Environment, Safety and Health Reporting"
DOE Order 252.1A, "Technical Standards Program"
DOE Order 410.1, "Central Technical Authority Responsibilities Regarding Nuclear Safety Requirements"
DOE Order 414.1D, "Quality Assurance"
DOE Order 420.1C, "Facility Safety"
DOE Order 420.2D, "Safety of Accelerators"
DOE Order 433.1B, "Maintenance Management Program for DOE Nuclear Facilities"
DOE Order 435.1, "Radioactive Waste Management"
DOE Order 440.1B, "Worker Protection Program for DOE (including National Nuclear Security Administration) Federal Employees"
DOE Manual 441.1-1, "Nuclear Material Packaging"
DOE Order 450.2, "Integrated Safety Management"
DOE Policy 451.1, "National Environmental Policy Act Compliance Program"
DOE Policy 454.1, "Use of Institutional Controls"
DOE Order 458.1, "Radiation Protection of the Public and the Environment"
DOE Order 460.1D, "Hazardous Materials Packaging and Transportation Safety"
DOE Order 460.2B, "Departmental Materials Transportation Management"

C.2.1.2 Energy Reorganization Act of 1974, as amended

The Energy Reorganization Act of 1974 divided the former AEC and created the ERDA and the NRC. The ERDA was responsible for radiation protection at its facilities to provide for worker and public health, worker safety, and environmental protection. The ERDA was abolished with the creation of the DOE in 1977.

C.2.1.2.1 Department of Energy Organization Act of 1977

The Department of Energy Organization Act of 1977 created the DOE by combining the ERDA, Federal Energy Administration, Federal Power Commission, and part of the U.S. Department of the Interior.

The DOE was intended to identify potential environmental, health, safety, socioeconomic, institutional, and technological issues associated with the development and use of energy sources. Through this law, the DOE retained the responsibilities and authorities—held by its predecessor agencies—to take actions necessary to protect the public from radiation associated with radioactive materials production, research, and development. The DOE established requirements through a directives system that largely used DOE orders as its regulatory procedures. With the passage of the Price-Anderson Amendments Act of 1988, the DOE began converting its health and safety orders to promulgated regulations.

C.2.1.3 Uranium Mill Tailings Radiation Control Act of 1978, as amended

UMTRCA provides a program of assessment and remedial action at active and inactive uranium mill sites to control their tailings in a safe and environmentally sound manner and to reduce radiation hazards to the public residing in the vicinity of these sites. The DOE was directed to complete remedial action at 21 sites of inactive uranium mills. Several additional sites have been added to the program since the enactment of UMTRCA.

C.2.1.4 West Valley Demonstration Project Act of 1980

This act authorized the DOE to carry out a project at West Valley, New York, to demonstrate solidification techniques that could be used for preparing high-level radioactive waste for disposal. The act provides for informal review and project consultation by the NRC. Since 1980, the DOE and its contractors have completed significant work at the site, including successful vitrification (solidification) and storage of high-level radioactive waste.

C.2.1.5 Low-Level Radioactive Waste Policy Act of 1980

This act and its 1985 amendments (see **Section C.2.1.7**) established the policy that each State is responsible for providing for the disposal of low-level radioactive waste generated within its borders, except for waste from defense activities of the DOE or Federal research and development activities. The act authorized States to enter into compacts to carry out this policy. The DOE was required to assist the States in carrying out this policy.

C.2.1.6 Nuclear Waste Policy Act of 1982, as amended

This act gives the DOE the responsibility to develop repositories and to establish a program of research, development, and demonstration for the disposal of high-level radioactive waste and spent nuclear fuel. Title to and custody of commercial low-level waste sites under certain conditions could be transferred to the DOE.

C.2.1.7 Low-Level Radioactive Waste Policy Amendments Act of 1985

This act amends the Low-Level Radioactive Waste Policy Act of 1980 to improve the procedures for State compacts. It also assigns responsibility to the Federal Government for the disposal of low-level waste generated or owned by the DOE, specific other federally generated or owned wastes, and wastes with concentrations of radionuclides that exceed the limits established by the NRC for Class C radioactive waste. The act provides that all Class C radioactive wastes designated as a Federal responsibility—those that result from activities licensed by the NRC—shall be disposed of in a facility licensed by the NRC. The act also assigns responsibilities to the DOE to provide financial and technical assistance to the States in carrying out the act.

C.2.1.8 Waste Isolation Pilot Plant Land Withdrawal Act of 1992

The Waste Isolation Pilot Plant (WIPP) is a repository intended for the disposal of transuranic radioactive waste produced by defense activities. The act establishes the following:

- an isolated parcel of land for the WIPP
- provisions concerning testing and limits on the quantities of waste that may be disposed at the WIPP
- EPA certification of compliance with disposal standards

C.2.1.9 Price-Anderson Amendments Act of 1988

The Price-Anderson Amendments Act (commonly called the Price-Anderson Act) is a Federal law covering liability-related issues for all nonmilitary nuclear facilities constructed in the United States before 2026.

C.2.2 Executive Orders

Executive Order 12580, “Superfund Implementation,” dated January 23, 1987, delegates to various Federal officials the responsibilities vested in the President for implementing CERCLA, as amended by the Superfund Amendments and Reauthorization Act of 1986.

C.2.3 DOE Regulations and Orders

C.2.3.1 10 CFR Part 835, “Occupational Radiation Protection”

This rule, which became effective on January 13, 1993, provides for the protection of radiation workers at DOE-owned facilities. The requirements in 10 CFR Part 835 are generally similar to those in NRC regulations pertaining to the commercial nuclear industry. In addition to the rule, the DOE issued a dozen implementation guides, including DOE-STD-1098, “Radiological Control,” dated January 31, 2017 (DOE 2017), and other supporting documents.

The DOE has developed guides, standards, and handbooks to assist in implementing the requirements of 10 CFR Part 835, including the following:

- DOE G 441.1-1C, Change 1 (Admin Chg), “Radiation Protection Programs Guide for Use with Title 10, *Code of Federal Regulations*, Part 835, Occupational Radiation Protection,” July 8, 2011 (DOE 2011a)

- DOE-STD-1095, “Department of Energy Laboratory Accreditation Program for Personnel Dosimetry,” dated January 21, 2025 (DOE 2025)

- DOE-STD-1098, “Radiological Control,” January 21, 2017 (DOE 2017)

- DOE-STD-1111, “Department of Energy Laboratory Accreditation Program Administration,” September 7, 2018 (DOE 2018)

- DOE-STD-1112, “Department of Energy Laboratory Accreditation Program for Radiobioassay,” August 1, 2019 (DOE 2019a)

- DOE-STD-1121, “Internal Dosimetry,” reaffirmed November 1, 2022 (DOE 2022a)

- DOE-HDBK-1122, Chg Notice 2, “Radiological Control Technician Training,” March 11, 2011 (DOE 2011b)

- DOE-STD-1128, “Good Practices for Occupational Radiological Protection in Plutonium Facilities,” reaffirmed January 31, 2020 (DOE 2020)

- DOE-STD-1129, “Tritium Handling and Safe Storage,” September 16, 2015 (DOE 2015)

- DOE-HDBK-1130, “Radiological Worker Training,” November 8, 2022 (DOE 2022b)

- DOE-STD-1136, “Good Practices for Occupational Radiological Protection in Uranium Facilities,” reaffirmed May 8, 2024 (DOE 2024)

C.2.3.2 DOE Order 458.1, “Radiation Protection of the Public and the Environment”

This order, issued in February 2011 (DOE 2011c), contains the requirements to protect the public and the environment against undue risk from radiation associated with radiological activities conducted under the DOE’s control. This regulation includes the following objectives:

- Conduct DOE radiological activities so that exposure to members of the public is kept within the dose limits established in the order.

- Control the radiological clearance of DOE real and personal property.

- Ensure that DOE sites have the capabilities, consistent with the types of radiological activities conducted, to monitor routine and nonroutine radiological releases and to assess the radiation dose to members of the public.

- Protect the environment from the effects of radiation and radioactive material.

The DOE has also developed a number of standards and handbooks to assist in implementing the requirements of DOE Order 458.1, including the following:

- DOE-STD-1153, “A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota,” February 12, 2019 (DOE 2019b)

- DOE-STD-1196, “Derived Concentration Technical Standard,” December 8, 2022 (DOE 2022c)
- DOE-HDBK-1216, Chg Notice 1, “Environmental Radiological Effluent Monitoring and Environmental Surveillance,” reaffirmed October 6, 2022 (DOE 2022e)
- DOE-STD-1241, “Implementing Release and Clearance of Property Requirements,” March 1, 2023 (DOE 2023)
- DOE-STD-6004, “Clearance and Release of Personal Property from Accelerator Facilities,” May 19, 2016 (DOE 2016)

C.2.3.2.1 Residual Radioactive Family of Codes

Argonne National Laboratory developed and maintains the residual radioactive (RESRAD) family of codes. Five codes are currently active: RESRAD-Onsite, RESRAD-Offsite, RESRAD-Build, RESRAD-RDD, and RESRAD-Biota. These codes are used to evaluate radiation exposure and risks. Many domestic and foreign agencies use these codes to derive cleanup criteria.

C.2.3.2.2 DOE Order 435.1, “Radioactive Waste Management”

DOE Order 435.1, “Radioactive Waste Management,” reaffirmed January 11, 2021 (DOE 2021), establishes the policies, guidelines, and requirements by which the DOE manages its radioactive and mixed waste and contaminated facilities. The order implements the DOE’s responsibilities and authorities for protection of public and worker health and safety and the environment under the AEA. It contains the requirements for management and disposal of low-level waste, including waste from the decommissioning of radioactively contaminated facilities.

C.3 U.S. Nuclear Regulatory Commission Regulations and Requirements

C.3.1 NRC Mission and Statutory Authority

The mission of the NRC is to ensure adequate protection of public health and safety, the common defense and security, and the environment in the use of nuclear materials in the United States. The NRC’s scope of responsibility includes regulation of commercial nuclear power reactors; nonpower research, test, and training reactors; fuel cycle facilities; medical, academic, and industrial uses of nuclear materials; and the storage and disposal of nuclear materials and waste.

The NRC is an independent agency created by the Energy Reorganization Act of 1974. This act abolished the AEC, moved the AEC’s regulatory function to the NRC, and, along with the AEA, provides the foundation for regulation of the Nation’s commercial nuclear power industry.

NRC regulations are issued under 10 CFR, Chapter I. The following principal statutory authorities govern the NRC’s work:

- Administrative Procedure Act of 1946
- Atomic Energy Act of 1954, as amended
- National Environmental Policy Act of 1969, as amended
- Energy Reorganization Act of 1974, as amended
- Uranium Mill Tailings Radiation Control Act of 1978, as amended
- Nuclear Non-Proliferation Act of 1978, as amended
- Low-Level Radioactive Waste Policy Act of 1980
- West Valley Demonstration Project Act of 1980
- Nuclear Waste Policy Act of 1982, as amended
- Low-Level Radioactive Waste Policy Amendments Act of 1985
- Omnibus Diplomatic Security and Antiterrorism Act of 1986
- Nuclear Waste Policy Amendments Act of 1987
- Solar, Wind, Waste, and Geothermal Power Production Incentives Act of 1990
- Energy Policy Act of 1992
- Energy Policy Act of 2005

The NRC and its licensees share a common responsibility to protect public health and safety and the environment. Federal regulations and the NRC regulatory program are important elements in the protection of the public and the environment. NRC licensees, however, have the primary responsibility for the safe use of nuclear materials.

C.3.2 NRC Criteria for Decommissioning

This section contains information on the existing cleanup criteria for decommissioning sites regulated by the NRC. Additional cleanup criteria established by State and local governments also may apply at NRC-licensed sites at the time of decommissioning.

The NRC's requirements for decommissioning and license termination are contained in 10 CFR 30.36, 40.42, 50.82, 70.38, and 72.54. Subpart E, "Radiological Criteria for License Termination," to 10 CFR Part 20, "Standards for Protection Against Radiation," also known as the License Termination Rule, provides criteria for both unrestricted and restricted release. According to 10 CFR 20.1402, "Radiological criteria for unrestricted use," a site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a total effective dose equivalent to an average member of the critical group that does not exceed 0.25 millisievert (mSv) (25 millirem [mrem]) per year, including that from groundwater sources of drinking water, and other requirements as applicable. The criteria for license termination with restrictions on future land use are described in 10 CFR 20.1403, "Criteria for license termination under restricted conditions." Under certain conditions, the restricted release criteria allow a limit of 0.25 mSv per year (y) (25 mrem/y) with restrictions in place, and 1.0 mSv/y (100 mrem/y) or 5.0 mSv/y (500 mrem/y) with no restrictions in effect.

The NRC's primary decommissioning guidance is found in the three volumes of NUREG-1757, "Consolidated Decommissioning Guidance." The first volume (NRC 2006) focuses on the decommissioning process for materials sites, while the second volume (NRC 2022a) focuses on the technical aspects of decommissioning, including dose modeling to derive cleanup levels and radiological surveys. Volume 2 applies to all licensees subject to the NRC's License Termination Rule found in 10 CFR Part 20, Subpart E, including reactor licensees. The third volume (NRC 2012a) focuses on financial assurance requirements in the NRC's regulations.

Other documents that were used in the past and that may continue to apply in special cases include Appendix A, "Criteria Relating to the Operation of Uranium Mills and the Disposition of Tailings or Wastes Produced by the Extraction or Concentration of Source Material from Ores Processed Primarily for Their Source Material Content," to 10 CFR Part 40, "Domestic Licensing of Source Material," as well as Subpart D, "Standards for Management of Uranium Byproduct Materials Pursuant to Section 84 of the Atomic Energy Act of 1954, as Amended," and Subpart E, "Standards for Management of Thorium Byproduct Materials Pursuant to Section 84 of the Atomic Energy Act of 1954, as Amended," of 40 CFR Part 192. These regulations, issued by the NRC and the EPA, establish technical criteria related to the operation, decontamination, decommissioning, and reclamation of uranium or thorium mills and mill tailings. Both regulations provide design requirements for closure of the mill's waste disposal area, which mandate an earthen cover over tailings or waste piles to control radiological hazards from uranium and thorium tailings for 200 to 1,000 years, according to Technical Criterion 6 of Appendix A to 10 CFR Part 40. The principal radiological hazards from uranium milling operations and mill tailings disposal are radon from uranium and thorium daughters. Criterion 6 includes details on the allowable radon release rates, which can be averaged[3] over a period of at least 1 year (but much less than 100 years) to account for the wide variability in atmospheric radon concentrations over short time periods and seasons. In addition, this criterion does not include radon emissions from earthen materials used to cover the tailings piles. If appropriate, radon emissions from cover materials are evaluated when developing a closure plan for each site to account for this additional contribution from naturally occurring radon.

C.3.3 NRC Decommissioning Process and Staff Plans for Implementing Survey Procedures in This Manual

NRC licensees are required to conduct radiation surveys of the premises where the licensed activities were conducted and submit a report describing the survey results. The survey process follows requirements in 10 CFR 30.36, 40.42, 50.82, 70.38, and 72.54, which pertain to decommissioning of a site and termination of a license. Each year, the NRC staff routinely evaluates licensee requests to discontinue licensed operations. Most of these requests are straightforward, requiring little, if any, site remediation before radiological surveys are conducted and evaluated. However, some NRC sites require substantial remediation because buildings and lands contain increased amounts of radiological contamination. The NRC may perform radiological surveys at legacy sites where there is not a license.

The NRC decommissioning process for a site requiring substantial remediation involves the following activities:

- licensee notification to the NRC that it intends to decommission all or part of the site
- site characterization, including preparation of the characterization plan and performance of site characterization
- development and submission of a decommissioning plan or license termination plan
- NRC review and approval of the decommissioning plan or license termination plan

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[3] In MARSSIM, "average" and "mean" both refer to the arithmetic mean.

- performance of decommissioning actions described in the plan
- performance of a final status survey and submittal of a final status survey report
- NRC performance and documentation of a confirmatory survey
- NRC termination of license

The NRC staff plans to use the information in this manual as primary guidance for conducting radiological surveys in response to routine licensee requests for license termination and nonroutine license termination requests that require more extensive decommissioning actions. The staff may use supplementary guidance to assist licensees in conducting such surveys or aid the staff in evaluating licensee survey plans and survey results to determine compliance with decommissioning criteria. Examples of supplementary guidance include NRC information notices, bulletins, generic letters, NUREG reports, regulatory guides, and other regulatory documents that transmit NRC requirements and guidance.

C.4 U.S. Department of Defense Regulations and Requirements

The U.S. Department of Defense (DoD) consists of the Office of the Secretary of Defense, Military Departments (U.S. Army, U.S. Navy, and U.S. Air Force), the Office of the Chairman of the Joint Chiefs of Staff and the Joint Staff, the Combatant Commands, the Office of the Inspector General of the Department of Defense, the Defense Agencies, the DoD Field Activities, and all other organizational entities within the DoD (collectively, the “DoD Components”).

The DoD Components use sources of ionizing radiation and support radiation protection programs for the control of these radioactive materials. As a Federal agency, the DoD complies with all applicable environmental regulations under the Federal Facilities Compliance Act of 1992.

C.4.1 DoD Authorities

The Military Application of Atomic Energy Authority, Section 91b of the AEA, provides authority for the President to direct the AEC to authorize DoD Components to acquire specified quantities of special nuclear material and utilization facilities for military purposes.

Additionally, in accordance with CERCLA, the DoD Components constitute the lead Federal agency responsible for addressing sites under several Federal environmental programs. The Formerly Used Defense Sites Program, Formerly Utilized Sites Remedial Action Program, and Defense Environmental Restoration Program are a few examples of such programs.

Each service has directives, regulations, and instructions for the management of the above authorities.

C.4.2 DoD Sources of Ionizing Radiation

The DoD’s list of radioactive materials includes the following:

- special nuclear material such as plutonium or enriched uranium
- source material such as uranium or thorium

- byproduct material such as any radioactive material yielded in or made radioactive by exposure to radiation incident to the process of producing special nuclear material

- naturally occurring radioactive material or accelerator-produced radioactive material, such as radium, and not classified as source material

- materials containing induced or deposited radionuclides

Electronic devices capable of emitting ionizing radiation, or devices that produce ionizing radiation, include linear accelerators, cyclotrons, radiofrequency generators that use klystrons or magnetrons, and other electron tubes that produce x-rays. These devices may have components that contain radioactive material, or they may induce radioactivity in certain other materials.

C.4.3 Commodities Containing Radioactive Material within the DoD System

The DoD uses a variety of manufactured items (commodities) incorporating in whole or in part both sealed and unsealed radioactive material. A sealed source is any radioactive material that is permanently bound or fixed in a capsule or matrix designed to prevent the release or dispersal of such material under the most severe conditions encountered in normal use.

Ionizing radiation is used directly in DoD systems as calibration and check sources for Radiac or other survey-type instruments, as a source of radioluminescence in meters and gauges, as an ionization source in various devices, and as radiographic sources.

Indirectly, ionizing radiation may be emitted from a DoD material system as natural radiation or induced radiation incorporated into material or a component of the system.

Specific examples of commodities include instrument calibration sources, luminescent compasses and exit signs, certain electron tubes and spark gaps, depleted uranium counterweights and munitions, and magnesium-thorium aircraft components.

C.4.4 Requirements Pertaining to NRC-Licensed Radioactive Material

Licensed radioactive material is source, special nuclear, or byproduct material received, stored, possessed, used, or transferred under a specific or general license issued by the NRC or an NRC Agreement State. All DoD Components control NRC-licensed materials either by a master materials license and permitting system or by specific NRC licenses issued to a particular agency.

For example, radioactive material may be licensed or controlled by the individual military services:

- The Department of the Air Force has been designated by the NRC, through the issuance of a Master Materials License, regulatory authority for the receipt, possession, distribution, use, transportation, transfer, and disposal of radioactive material for Air Force activities. The Air Force Radioisotope Committee was established to provide administrative control of all radioactive material used in the Air Force except for reactors and associated radioactivity, nuclear weapons, and certain components of weapons delivery systems. Air Force Radioactive Material Permits are used to maintain this control.

- The Department of the Army, through the issuance of NRC specific licenses to Army installations and activity commanders, maintains the regulatory authority for the receipt, possession, distribution, use, transportation, transfer, and disposal of radioactive material for Army activities. In addition, within the Department of the Army, radioactive material classified as naturally occurring accelerator-produced radioactive material may be used under a Department of the Army Radioactive Material Authorization issued by the Army Materiel Command or the Office of the Army Surgeon General. A Department of the Army Radiation Permit is required for use, storage, possession, and disposal of radiation sources by non-Army agencies (including contractors) on Army installations.

- The Department of the Navy is designated by the NRC to have, through the issuance of a Master Materials License, regulatory authority for the receipt, possession, distribution, use, transportation, transfer, and disposal of radioactive material for Navy and Marine Corps activities. The Navy Radiation Safety Committee was established to provide administrative control of all radioactive material used in the Navy and Marine Corps except for nuclear propulsion reactors and associated radioactivity, nuclear weapons, and certain components of weapons delivery systems. Navy Radioactive Material Permits are used to maintain this control.

C.4.5 Military Application of Atomic Energy

The U.S. Air Force, the U.S. Army, and the U.S. Navy possess radioactive materials under Section 91b, Chapter 9, “Military Application of Atomic Energy,” of the AEA (42 U.S.C. § 2121) that are excepted from NRC licensing requirements (42 U.S.C. § 2122). Each service has directives and instructions for the safe management of these materials.

C.4.6 Other Controlled Radioactive Material

Certain naturally occurring and accelerator-produced radioactive material possessed by the military services may not be subject to the AEA. Each DoD Component has directives and instructions for the safe management of these materials while under the responsibility of the DoD. For real property impacted by these radioactive materials and subject to base realignment and closure actions, the radioactive material may be subject to State limits, guidelines, and procedures. The methodologies and technical approaches for environmental radiological surveys outlined in this manual will provide guidance for dealing with issues concerning this material.

C.4.7 DoD Regulations Concerning Radiation and the Environment

The DoD, with its global mission, supports several directives and instructions concerning environmental compliance. The individual military services have regulations implementing these directives and instructions. The documents describing these regulations are used as guidance in developing environmental radiological surveys within the DoD.

The DoD Components also have specific regulations addressing the use of radioactive sources and the development of occupational health programs and radiation protection programs. These regulations may help in identifying potential locations and sources of residual radioactive material on DoD installations.

Commodities also are used in military medical treatment facilities within the United States and military bases overseas. Military hospitals use radioactive commodities for quality assurance/quality control of medical equipment, diagnostic tools, and therapy treatments.

C.4.8 DoD Regulations and Requirements for the Development of Environmental Radiological Surveys

The following regulations and requirements concern the development of environmental radiological surveys:

- DoD Instruction 4715.05, Incorporating Change 2, "Environmental Compliance at Installations Outside the United States," August 31, 2018 (DoD 2018a)
- DoD Instruction 4715.23, Change 1, "Integrated Recycling and Solid Waste Management," August 31, 2018 (DoD 2018b)
- DoD Directive 4715.1E, Change 2, "Environment, Safety, and Occupational Health (ESOH)," December 30, 2019 (DoD 2019)

The following regulations and requirements concern the use of radioactive sources and development of occupational health programs and radiation protection programs:

- DoDM 6055.05, "Occupational Medical Examinations: Medical Surveillance and Medical Qualification," July 27, 2022, Change 1, effective April 5, 2024 (DoD 2024)
- DoD Instruction 6055.08, "Occupational Ionizing Radiation Protection Program," effective April 9, 2021 (DoD 2021)

The following are examples of Air Force instructions (AFIs):

- AFMAN 40-201, "Radioactive Materials (RAM) Management," February 2024 (DAF 2024)
- AFI 32-7020, "Environmental Restoration Program," March 2020 (DAF 2020)
- AFI 32-7066, "Environmental Baseline Surveys in Real Property Transactions," January 2015 (DAF 2015)

The following are examples of Army regulations (ARs) and other requirements:

- AR 385-10, "The Army Safety and Occupational Health Program," July 24, 2023 (Army 2023a)
- DA PAM 385-10, "The Army Safety and Occupational Health Program Procedures," July 24, 2023 (Army 2023b)
- AR 40-5, "Army Public Health Program," May 12, 2020 (Army 2020a)
- AR 40-10, "Health Hazard Assessment Program in Support of the Army Acquisition Process," July 2007 (Army 2007a)
- DA PAM 40-11, "Army Public Health Program," May 18, 2020 (Army 2020b)
- AR 200-1, "Environmental Protection and Enhancement," December 2007 (Army 2007b)
- AR 700-48, "Management of Radiologically Contaminated Equipment Outside the United States," August 12, 2020 (Army 2020c)

- DA PAM 700-48, “Handling Procedures for Equipment Contaminated by Radioactive Commodities,” March 5, 2021 (Army 2021)
- AR 750-43, “Army Test, Measurement, and Diagnostic Equipment,” effective July 15, 2024 (Army 2024a)
- TB MED 521, “Occupational and Environmental Health: Management and Control of Diagnostic, Therapeutic, and Medical Research X-Ray Systems and Facilities,” February 2002 (Army 2002)
- TB MED 522, “Occupational and Environmental Health: Control of Health Hazards from Protective Material Used in Self-Luminous Devices,” August 1980 (Army 1980)
- TB MED 525, “Control of Hazards to Health from Ionizing Radiation Used by the Army Medical Department,” March 1988 (Army 1988a)
- TB 43-180, “Calibration and Repair Requirements for the Maintenance of Army Materiel,” effective September 1, 2024 (Army 2024b)
- TB 43-0116, “Identification of Radioactive Items in the Army,” April 1998 (Army 1998)
- TB 43-0122, “Identification of U.S. Army Communications-Electronics Command-Managed Radioactive Items in the Army Supply System,” February 1989 (Army 1989a)
- TB 43-0197, “Instructions for Safe Handling, Maintenance, Storage and Transportation of Radioactive Items under License 12-00722-06,” June 2006 (Army 2006)
- TB 43-0216, “Safety and Hazard Warnings for Operation and Maintenance of TACOM Equipment,” October 1990 (Army 1990)
- TM 3-261, “Handling and Disposal of Unwanted Radioactive Material,” May 1988 (Army 1988b)
- TM 55-315, “Transportability Guidance for Safe Transport of Radioactive Materials,” June 1989 (Army 1989b)

The following are examples of Navy regulations:

- NAVMED P-5055, Incorporating Change 1, “Radiation Health Protection Manual,” April 2018 (Navy 2018)
- NAVSEA S0420-AA-RAD-010, Revision 2A, “Radiological Affairs Support Program (RASP) Manual,” May 2019 (Navy 2019)
- OPNAVINST 6470.3, “Navy Radiation Safety Committee,” July 2015 (Navy 2015)
- NAVSEA 5100.18B, “Radiological Affairs Support Program,” February 2007 (Navy 2007)
- BUMEDINST 6470.10C, “Initial Management of Irradiated or Radioactively Contaminated Personnel,” February 2021 (Navy 2021)

C.5 State and Local Regulations and Requirements

An Agreement State is a State that has assumed authority to regulate byproduct, source, and small quantities of special nuclear material that has been relinquished by the NRC in accordance with Section 274b. of the AEA. **Table C-2** lists the Agreement States as of February 5, 2024. Each Agreement State provides regulations governing the use of radioactive materials that may relate to radiation site investigations.[4] **Table C-3** lists the States that regulate naturally occurring radioactive material. The decision-maker should[5] check with the State to ensure compliance with all applicable regulations.

Table C-2 Agreement States as of February 5, 2024

Alabama	Maine	Oklahoma
Arizona	Maryland	Oregon
Arkansas	Massachusetts	Pennsylvania
California	Minnesota	Rhode Island
Colorado	Mississippi	South Carolina
Connecticut (letter of intent)	Nebraska	Tennessee
Florida	Nevada	Texas
Georgia	New Hampshire	Utah
Illinois	New Jersey	Vermont
Indiana (letter of intent)	New Mexico	Virginia
Iowa	New York	Washington
Kansas	North Carolina	West Virginia (letter of intent)
Kentucky	North Dakota	Wisconsin
Louisiana	Ohio	Wyoming

Table C-3 States that Regulate Diffuse Naturally Occurring Radioactive Material

Alabama (proposed)	Michigan	North Dakota
Arkansas	Mississippi	Ohio
Colorado	Montana	Oregon
Georgia	New Jersey	South Carolina
Illinois	New Mexico	Texas
Louisiana	New York	Utah

[4] A current list of Agreement States can be obtained through the NRC website at https://www.nrc.gov/agreement-states.html.

[5] MARSSIM uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

APPENDIX D
MARSSIM PROJECT-LEVEL QUALITY SYSTEM COMPONENTS

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides detailed guidance for planning, implementing, and evaluating environmental and facility radiological surveys conducted to demonstrate compliance with a dose- or risk-based regulation. The guidance focuses on demonstrating compliance during the final status survey (FSS) following scoping, characterization, and any necessary remedial actions.

MARSSIM requires that all environmental data collection and use take place in accordance with a site-specific systematic planning process that incorporates industry-established quality assurance (QA)/quality control (QC). The goal of a QA/QC program is to identify and implement sampling and analytical methodologies that limit uncertainty in the analytical data. For MARSSIM data collection and evaluation, a quality system is needed to ensure that radiation surveys produce results that are of the type and quality needed and expected for their intended use. A quality system is a management system that describes the elements necessary to plan, implement, and assess the effectiveness of QA/QC activities. This system establishes many functions, including quality management policies and guidelines for the development of organization- and project-specific quality plans, criteria and guidelines for assessing data quality, assessments to ascertain effectiveness of QA/QC implementation, and training programs related to QA/QC implementation. A quality system ensures that MARSSIM decisions will be supported by sufficient data of adequate quality and usability for their intended purpose, and it further ensures that such data are authentic, appropriately documented, and technically defensible. MARSSIM uses the project-level components of a quality system as a framework for planning, implementing, and assessing environmental data collection activities.

Appendix D includes the following elements of the quality system process:

- Planning is carried out through the implementation of the Data Quality Objectives (DQO) process, in which planning steps for establishing a survey design are identified and MARSSIM-specific aspects of the planning process are established. The DQO process is a series of planning steps based on the scientific method for establishing criteria for data quality and developing survey designs (EPA 2006c, 1987a, 1987b) (**Section D.1**).

- The result of the DQO process is a scientifically justifiable survey design. Based on the established design, a Quality Assurance Project Plan (QAPP) is established in the framework of an environmental quality system, the elements of which are outlined in the Uniform Federal Policy for Implementing Environmental Quality Systems (UFP-QS) (EPA 2005a). A QAPP that integrates all technical and quality aspects and defines in detail how specific QA and QC activities will be implemented during the survey project will be developed based on the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP) (EPA 2005b) (**Section D.2**).

- Data Quality Assessment (DQA) is the scientific and statistical evaluation of data to determine whether the data are of the right type, quality, and quantity to support their intended use (EPA 2006a, 2006b). DQA provides the assessment needed to determine that the planning objectives are achieved (**Section D.3**).

- The assessment phase includes verification and validation of the survey data and assessment of data quality. Data verification and validation is the process of evaluating

the quality of the data collected for a survey to determine whether the data are appropriate for use in the assessment process and for decision-making (**Section D.4**).

Much of this appendix is written from the perspective of Scenario A, but it also includes important considerations for Scenario B. Details on the project-level components for planning and assessing environmental collection activities are provided in this appendix, as well as in **Chapters 2, 3, 4, 5, and 8.** MARSSIM **Chapters 6** and **7** and **Appendix H** contain guidance on selecting appropriate measurement techniques (i.e., scan surveys, direct measurements, samples) and measurement systems (i.e., detectors, instruments) for implementing the survey design.

D.1 The Planning Phase

The DQO process is a series of planning steps based on the scientific method for establishing criteria for data quality and developing survey designs (EPA 2006c, 1987b, 1987c). The level of effort associated with planning is based on the complexity of the survey. Large, complicated sites generally receive a significant amount of effort during the planning phase, while smaller sites may not require as much planning effort.

Planning radiological surveys using the DQO process can improve survey effectiveness and efficiency, and thus the defensibility of decisions. It can also minimize expenditures related to data collection by eliminating unnecessary, duplicative, or overly precise data. Use of the DQO process ensures that the type, quantity, and quality of environmental data used in decision-making will be appropriate for the intended application. It provides systematic procedures for defining the criteria that the survey design should[1] satisfy, including when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform.

The DQO process provides for early involvement of the decision-maker and uses a graded approach to data quality requirements. This graded approach defines data quality requirements according to the type of survey being designed, the risk of making a decision error based on the data collected, and the consequences of making such an error. This approach provides a more effective survey design combined with a basis for judging the usability of the data collected.

DQOs are qualitative and quantitative statements derived from the outputs of the DQO process that do the following:

- Clarify the study objective.
- Define the most appropriate type of data to collect.
- Determine the most appropriate conditions for collecting the data.
- Specify limits on decision errors that will be used as the basis for establishing the quantity and quality of data needed to support the decision.

The DQO process consists of seven steps, as shown in **Figure D-1** (EPA 2006c).

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[1] MARSSIM uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

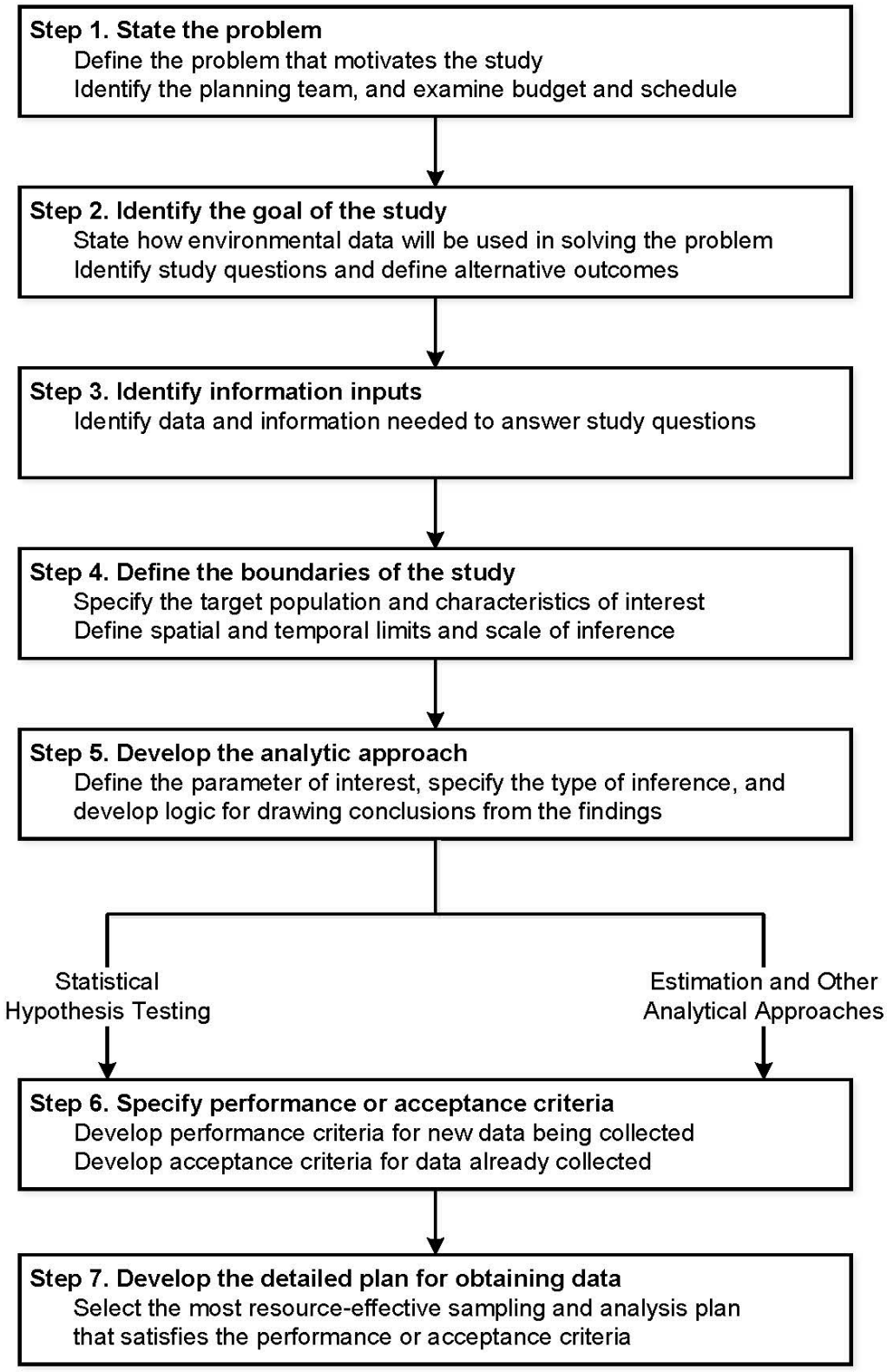

Figure D-1 The DQO Process

The output from each step influences the choices that will be made later in the process. Even though the DQO process is depicted as a linear sequence of steps, in practice it is iterative; the outputs of one step may lead to reconsideration of prior steps, as illustrated in **Figure D-2**. For example, defining the survey unit boundaries may lead to classification of the survey unit, with each survey unit having a different decision statement. This iteration is encouraged because it ultimately leads to a more efficient survey design. The first six steps of the DQO process produce the decision performance criteria that are used to develop the survey design. The final step of the process develops a survey design based on the DQOs. The first six steps should be completed before the final survey design is developed, and every step should be completed before data collection begins.

When the DQO process is used to design a survey, it helps to ensure that planning is performed properly the first time. It establishes measures of performance for the data collector (implementation) and the decision-maker (assessment) during subsequent phases. DQOs provide up-front planning and define decision-maker/data collector relationships by presenting a clear statement of the decision-maker's needs. This information is recorded in the QAPP.

DQOs for any data collection activity describe the overall level of uncertainty that a decision-maker is willing to accept for survey results. DQOs are a statement of a performance objective or requirement for a particular characteristic that is expressed in terms of data quality indicators (DQIs) for precision (indicating random measurement error), bias (indicating systematic measurement error), accuracy, representativeness and measurement detectability, comparability, and completeness. **Section D.4.2.6** presents these indicators in detail.

Measurement Quality Objectives (MQO) are a subset of the DQOs that address quality objectives for the selection of field and laboratory measurement systems. They provide quantitative performance or acceptance criteria for DQIs. The primary MQOs that are evaluated in a measurement survey include the following:

- measurement method uncertainty
- detection capability
- range
- specificity
- ruggedness

Section D.1.7.2 presents additional detail on MQOs.

The DQO process is a flexible planning tool that can be used as intensively as the situation requires. For surveys that have multiple decisions, such as characterization surveys or FSSs, the DQO process can be used repeatedly throughout the performance of the survey. Decisions made early in decommissioning are often preliminary in nature. For this reason, a scoping survey may require only a limited planning and evaluation effort. As the site investigation process nears its conclusion, the necessity of avoiding a decision error becomes more critical.

The following sections briefly discuss the steps of the DQO process, especially as they relate to FSS planning, and list the outputs for each step in the process. The outputs from the DQO process should be included in the documentation for the survey plan. **Section D.1.7.2** provides additional detail on MQOs.

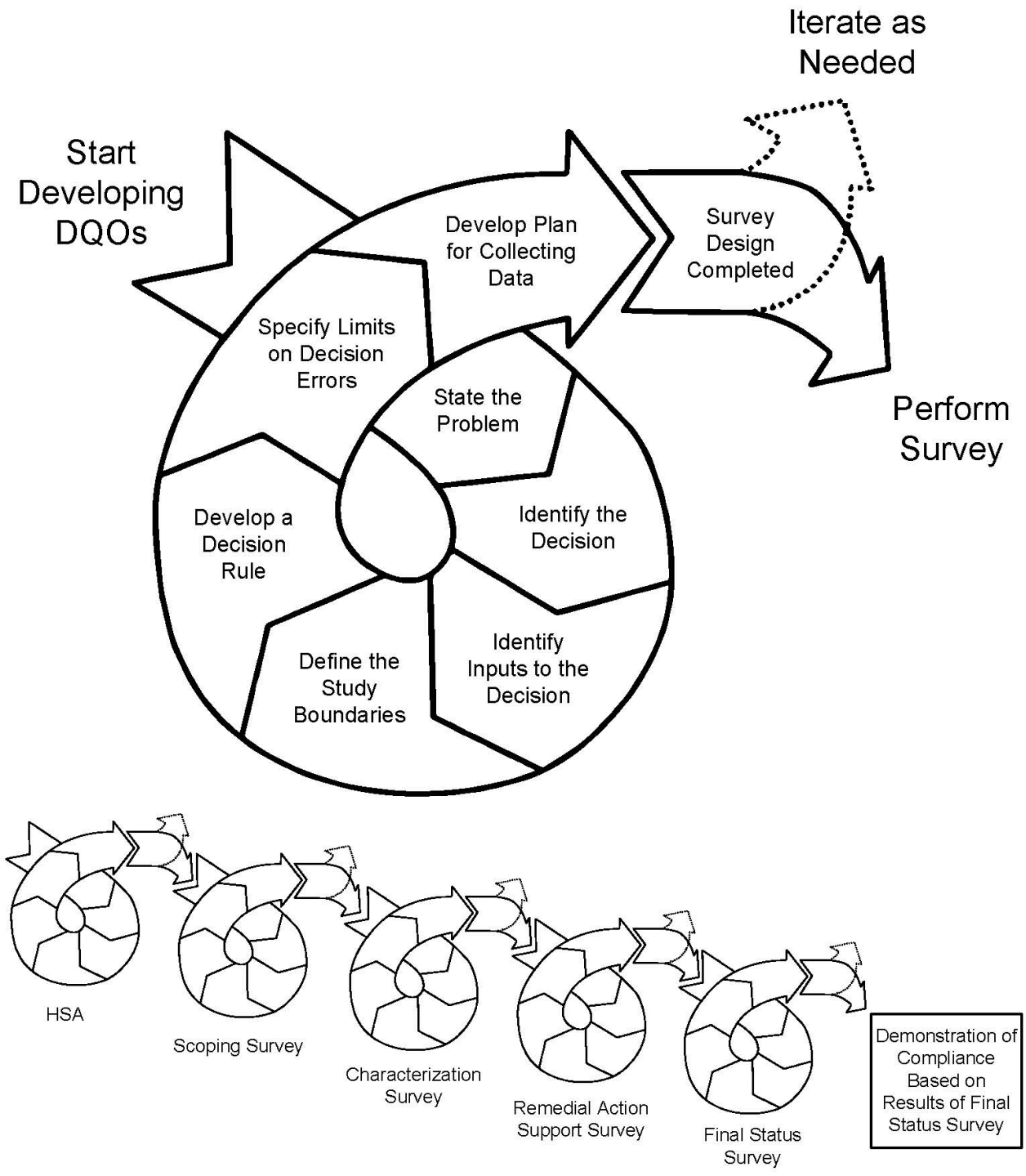

Figure D-2 Repeated Application of the DQO Process throughout the Radiation Survey and Site Investigation Process

D.1.1 State the Problem

The first step in any decision-making process is to define the problem so that the focus of the survey will be unambiguous. Because many sites or facilities present a complex interaction of technical, economic, social, and political factors, the success of a project is critically linked to a complete but uncomplicated definition of the problem.

Four activities are associated with this step:

(1) Identify members of the planning team and stakeholders.
(2) Identify the primary decision-maker or decision-making method.
(3) Develop a concise description of the problem.
(4) Specify available resources and relevant deadlines for the study.

This step results in the following expected outputs:

- a list of the planning team members and identification of the decision-maker
- a concise description of the problem
- a summary of available resources and relevant deadlines for the survey

Section 3.2 gives examples of planning team members and stakeholders for an FSS. A description of the problem would typically involve the release of all or some portion of a site to demonstrate compliance with a regulation. The resources and deadlines are typically identified on a site-specific basis.

D.1.2 Identify the Goals of the Study

The purpose of this step is to define the question that the survey will attempt to resolve and identify alternative actions that may be taken based on the outcome of the survey. The combination of these two elements is called the decision statement. The decision statement would be different for each type of survey in the Radiation Survey and Site Investigation (RSSI) process and would be developed based on the survey objectives described in **Chapter 5.** Four activities are associated with this step in the DQO process:

(1) Identify the principal study question.

(2) Define the alternative actions that could result from resolution of the principal study question.

(3) Combine the principal study question and the alternative actions into a decision statement.

(4) Organize multiple decisions.

The expected output from this step is a decision statement that links the principal study question to possible solutions to the problem. For an FSS, the principal study question could be, “Is the level of residual radioactive materials in the survey units in this portion of the site below the release criteria?” Alternative actions may include further remediation, reevaluation of the modeling assumptions used to develop the derived concentration guideline levels (DCGLs), reassessment of the survey unit to see whether it can be released with passive controls, or a decision not to release the survey unit. The decision statement may be, “Determine whether all the survey units in this portion of the site satisfy the release criteria.”

D.1.3 Identify Information Inputs

Collecting data or information is necessary to resolve most decision statements. In this step, the planning team focuses on the information needed for the decision and identifies the different types of information needed to resolve the decision statement. This step involves the following four key activities:

(1) Identify the information required to resolve the decision statement. Ask general questions, such as “Is information on the physical properties of the site required?” or “Is information on the chemical characteristics of the radionuclide or the matrix required?” Determine which environmental variables or other data are needed to resolve the decision statement.

(2) Determine and list the sources for each item of information.

(3) Identify the information needed to establish the DCGL or action level (AL) based on the release criteria. The actual numerical value will be determined in Step 5 (i.e., **Section D.1.5**).

(4) Confirm that appropriate measurement methods exist to provide the necessary data. A list of potentially appropriate measurement techniques should be prepared based on the information requirements determined previously in this step. **Chapters 6 and 7** discuss field and laboratory measurement techniques for radionuclides. **Appendix H** contains information on using field and laboratory equipment, their detection limits, and analytical costs. This performance information will be used in Steps 5 and 7 of the DQO process.

This step results in the following expected outputs:

- a list of information inputs needed to resolve the decision statement, and their sources
- a list of environmental variables or characteristics that will be measured according to available measurement techniques and measurement systems

For the FSS, the list of information inputs generally involves measurements of the residual radionuclides of concern in each survey unit. These inputs include identifying survey units, classifying survey units, identifying appropriate measurement techniques (including measurement costs and detection limits), and determining whether background measurements from a reference area or areas need to be performed. The list of environmental variables measured during the FSS is typically limited to the level of residual radioactive materials in the affected media for each survey unit.

D.1.4 Define the Boundaries of the Study

During this step, the planning team should develop a conceptual model of the site based on the existing information collected in Step 1 of the DQO process or during previous surveys. Conceptual models describe a site or facility and its environs and present hypotheses regarding the radionuclides present and potential migration pathways. These models may include components from computer models, analytical models, graphic models, and other techniques. Additional data collected during remediation are used to expand the conceptual model.

The purpose of this step is to define the spatial and temporal boundaries that will be covered by the decision statement, so data can be easily interpreted. These attributes include the following:

- spatial boundaries that define the physical area under consideration for release (site boundaries)
- spatial boundaries that define the physical area to be studied and locations where measurements could be performed (actual or potential survey unit boundaries)
- temporal boundaries that describe the time frame the study data represent and when measurements should be performed
- spatial and temporal boundaries developed from modeling used to determine DCGLs
- any practical, spatial, or temporal constraints on the data collection process

Seven activities are associated with this step:

(1) Specify characteristics that define the true but unknown value of the parameter of interest.

(2) Define the geographic area within which all decisions must apply.

(3) When appropriate, divide the site into survey units that have relatively homogeneous characteristics.

(4) Determine the time frame to which the decision applies.

(5) Determine when to collect data.

(6) Define the scale of decision-making.

(7) Identify any practical constraints on data collection.

This step results in the following expected outputs:

- a detailed description of the spatial and temporal boundaries of the problem (a conceptual model)
- any practical constraints that may interfere with the full implementation of the survey design

Specifying the characteristics that define the true but unknown value of the parameter of interest for the FSS typically involves identifying the radionuclides of concern. If possible, the physical and chemical forms of the radionuclides should be described. For example, describing the residual radioactive materials in terms of total uranium is not as specific or informative as describing a mixture of uraninite (UO_2) and uranium metaphosphate ($U(PO_3)_4$) for natural abundances of uranium-234, uranium-235, and uranium-238.

As another example, the study boundary may be defined as the property boundary of a facility or, if there is only surface radioactive material expected at the site, the soil within the property boundary to a certain specified depth, such as 15 centimeters. When appropriate (typically during and always before FSS design), the site is subdivided into survey units with relatively homogeneous characteristics based on information collected during previous surveys. The radiological characteristics are defined by the survey unit classification (Class 1, Class 2, or Class 3), whereas the physical characteristics may include structures versus land areas,

transport routes versus grassy areas, or soil types with different radionuclide transfer characteristics.

The time frame to which the FSS decision applies is typically defined by the regulation; for example, “The data are used to reflect the condition of radionuclides leaching into groundwater over a period of 1,000 years.” Temporal boundaries may also include seasonal conditions, such as winter snow cover or summer drought, that affect the accessibility of certain media for measurement. For the FSS, the smallest, most appropriate subsets of the site for which decisions will be made are defined as survey units.

The size of the survey unit and the density of samples within a survey unit are based on classification, site-specific conditions, and relevant decisions used during modeling to determine the DCGLs.

D.1.5 Develop the Analytic Approach

The purpose of this step is to define the parameter of interest, specify the AL (or DCGL), and integrate previous DQO outputs into a single statement that describes a logical basis for choosing among alternative actions.

Three activities are associated with this step:

(1) Specify the statistical parameter that characterizes the radionuclide(s) of interest.

(2) Specify the AL for each radionuclide of interest for the study.

(3) Combine the outputs of the previous DQO steps into an “if...then...” decision rule that defines the conditions that would cause the decision-maker to choose among alternative actions.

Certain aspects of the RSSI process, such as the Historical Site Assessment (HSA), are not so quantitative that a statistical parameter can be specified. Nevertheless, a decision rule should still be developed that defines the conditions that would cause the decision-maker to choose among alternatives.

This step results in the following expected outputs:

- the radionuclide(s) of interest that characterizes the level of residual radioactive material
- the AL for each radionuclide of interest
- an “if...then...” statement that defines the conditions that would cause the decision-maker to choose among alternative actions

The parameter of interest is a descriptive measure (such as a mean or median) that specifies the characteristic or attribute that the decision-maker would like to know about the residual radioactive material in the survey unit.

The mean is the value that corresponds to the “center” of the distribution in the sense of the “center of gravity” (EPA 1989b). Positive attributes of the mean include that (1) it is useful when the AL is based on long-term, average risk of health effects, (2) it is useful when the population is uniform with relatively small variance, and (3) it generally requires fewer samples than other parameters of interest. Negative attributes include that (1) the mean is not a very representative

measure of central tendency for highly skewed distributions, and (2) it is not useful when a large proportion of the measurements are reported as less than the detection limit (EPA 2006b).

The median is also a value that corresponds to the "center" of a distribution, but while the mean represents the center of gravity, the median represents the "middle" value of a distribution. The median is that value such that there are the same number of measurements greater than the median as less than the median. The positive attributes of the median include that (1) it is useful when the AL is based on long-term, average risk of health effects, (2) it provides a more representative measure of central tendency than the mean for skewed populations, (3) it is useful when a large proportion of the measurements are reported as less than the detection limit, and (4) it relies on few statistical assumptions.

The nonparametric statistical tests discussed in **Chapter 8** are designed to determine whether the level of residual radioactive material uniformly distributed throughout the survey unit exceeds the DCGL for average concentrations over a wide area ($DCGL_W$).[2] Because these methods are based on ranks, the results are generally expressed in terms of the median. When the underlying measurement distribution is symmetric, the mean is equal to the median. The assumption of symmetry is less restrictive than that of normality, because the normal distribution is itself symmetric. If, however, the measurement distribution is skewed to the right, the average will generally be greater than the median. In severe cases, the average may exceed the $DCGL_W$ while the median does not. For this reason, MARSSIM recommends comparing the mean of the survey unit data to the $DCGL_W$ as a first step in the interpretation of the data (**Section 8.2.2.1**).

The AL is a measurement threshold value of the parameter of interest that provides the criteria for choosing among alternative actions. MARSSIM uses the investigation level, a radionuclide-specific level of radioactive materials based on the release criteria that results in additional investigation when it is exceeded. **Section 5.3.8** provides information on the investigation levels used in MARSSIM.

The mean concentration of residual radioactive material is the parameter of interest used for making decisions based on the FSS. The definition of residual radioactive material depends on whether the radionuclide appears as part of background radioactive material in the reference area. If the radionuclide is not present in background, residual radioactive material is defined as the mean concentration in the survey unit. If the radionuclide *is* present in background, residual radioactive material is defined as the difference between the mean concentration in the survey unit and the mean concentration in the reference area selected to represent background. The Sign test is used when the radionuclide does not appear in background, because measurements are only made in the survey unit. The WRS test is used when the radionuclide appears in background, because measurements are made in both the survey unit and the reference area.

Decision-makers determine the requirements of the hypothesis test based on an evaluation of the consequences of making a Type I error or a Type II error. The interpretation of Type I and Type II errors depends on whether Scenario A or B has been selected. This section provides additional information for selecting between these two alternative hypothesis testing scenarios.

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[2] The "W" in $DCGL_W$ historically stood for Wilcoxon Rank Sum (WRS) test, which is the statistical test recommended in MARSSIM for demonstrating compliance when the radionuclide is present in background. However, as the Sign test is also a recommended test in MARSSIM for demonstrating compliance when the radionuclide is not present in background, the term now colloquially refers to "wide-area" or "average."

Historically, statisticians have noted that there is an asymmetry between the two types of errors:

> The justification for fixing the Type 1 error to be α (usually small and often taken as 0.05 or 0.01) seems to arise from those testing situations where the two hypotheses are formulated in such a way that one type of error is more serious than the other. The hypotheses are stated so that the Type 1 error is more serious, and hence, one wants to be certain that it is small. (Mood et al. 1974)

This opinion was echoed by Bickel and Doksum (1977), who use the symbol "H" for the null hypothesis (H_0 is used in this document) and "K" for the alternative (H_1 used in this document):

> Even when we leave the area of scientific research the relative importance of the errors we commit in hypothesis testing is frequently not the same. There is a general convention that, if the labeling of H and K is free, the label H is assigned so that type 1 error is the most important to the experimenter. (Bickel and Doksum 1977)

These opinions relate to the choice between Scenario A and Scenario B, which are distinguished by the reversal of the null and the alternative hypotheses, when the radionuclide concentration is to be compared to the DCGL. The two hypothesis testing scenarios are specified in mathematical terms as follows:

- Scenario A: H_0: $X > \text{DCGL}$ versus H_1: $X \leq \text{DCGL}$
- Scenario B: H_0: $X \leq \text{AL}$ versus H_1: $X > \text{AL}$

When the radionuclide does not appear in background, X represents the random concentration in the survey unit. When the radionuclide does appear in background, X represents the difference between the survey unit and reference area concentration distributions. Scenario A compares X to the DCGL using a null hypothesis that X exceeds the DCGL. The alternative hypothesis is the complement of the null hypothesis (i.e., that X does not exceed the DCGL). Scenario B is the opposite of Scenario A, using a null hypothesis that X does not exceed the AL. The alternative hypothesis for this scenario is that X exceeds the AL.

Section 3.1 of U.S. Environmental Protection Agency (EPA) QA/G-9R, "Data Quality Assessment: A Reviewer's Guide," issued February 2006 (EPA 2006a), provides the following guidance on the selection of an appropriate null hypothesis in choosing between Scenarios A and B:

> It is important to take care in defining the null and alternative hypotheses because the null hypothesis will be considered true unless the data demonstratively shows proof for the alternative. In layman's terms, this is equivalent of an accused person appearing in civil court; the accused is presumed to be innocent unless shown by the evidence to be guilty by a preponderance of evidence. Note the parallel: "presumed innocent" & "null hypothesis considered true", "evidence" & "data", "preponderance of evidence" & "demonstratively shows". It is often useful to choose the null and alternative hypotheses in light of the consequences of making an incorrect determination between them. The true condition that occurs with the more severe decision error is often defined as the null hypothesis thus making it hard to make this kind of decision error. The statistical hypothesis framework would rather allow a false acceptance than a false rejection. As with the accused and the assumption of innocence, the judicial system makes it difficult to convict an innocent person (the

evidence must be very strong in favor of conviction) and therefore allows some truly guilty to go free (the evidence was not strong enough). The judicial system would rather allow a guilty person to go free than have an innocent person found guilty.

Chapter 6 of EPA QA/G-4, "Guidance on Systematic Planning Using the Data Quality Objectives Process," issued February 2006 (EPA 2006c), is more succinct and definitive for deciding between Scenarios A and B:

- Define the null hypothesis (baseline condition) and the alternative hypothesis and assign the terms "false positive" and "false negative" to the appropriate decision error.

- In problems that concern regulatory compliance, human health, or ecological risk, the decision error that has the most adverse potential consequences should be defined as the null hypothesis (baseline condition). In statistical hypothesis testing, the data must conclusively demonstrate that the null hypothesis is false. That is, the data must provide enough information to authoritatively reject the null hypothesis (reject the baseline condition) in favor of the alternative. Therefore, by setting the null hypothesis equal to the true state of nature that exists when the more severe decision error occurs, the decision-maker guards against making the more severe decision error by placing the burden of proof on demonstrating that the most adverse consequences will not be likely to occur.

The reference to "burden of proof" suggests that environmental concerns are not like the jury trial process, and that the "innocent until proven guilty" assumption is an environmentally risky approach. From this viewpoint, a more protective approach would be to "presume guilt" and demand proof of innocence: "guilty until proven innocent."

This guidance adopts a conservative approach by stating that, when the results of the investigation are uncertain, erroneously concluding that the survey does not comply with the release criteria is preferable to concluding that the survey unit is in compliance with the release criteria when it actually is not. Again, the recommended approach favors protection of human health and the environment.

One condition in which selecting Scenario B is appropriate is when the release criteria are "indistinguishable from zero" or "no added radioactivity"—where the AL is effectively set to 0 or 0 above background. For this case in Scenario A, it is impossible to set a lower bound of the gray region (LBGR) that is physically distinct from the AL and, therefore, impossible to design a survey. This makes intuitive sense, as it is impossible to prove that an area is below an AL of 0 or 0 above background. When Scenario B is selected, a discrimination limit (DL) is set above the AL as the upper bound of the gray region (UBGR).

In addition to the differences between testing Scenarios A and B that are due to asymmetry of the decision errors, there also are differences due to statistical and administrative considerations.

The power of a statistical test ($1-\beta$) is a measure of its ability to reject the null hypothesis when it is false. The power of the test is determined by a few factors that are known only with uncertainty when the survey is designed. The power of the test is determined by the actual number of usable samples from the survey unit and reference area and the variances of these samples. Poor initial estimates of the variances or an unexpectedly large number of unusable samples may result in an insufficient sample size to provide the required power. The

consequences of inadequate power differ between Scenario A and Scenario B. In Scenario A, inadequate power means that survey units that actually meet the release criteria will have a higher chance of failing. In Scenario B, inadequate power means that survey units that actually exceed the release criteria will have a higher chance of going undetected. In this case, the survey unit may be released only because of an inadequate number of samples.

It is generally desirable for the statistical hypothesis test to have high power, and a well-executed survey will usually accomplish this. However, it is also generally true that a poorly designed and executed survey will result in a relatively high probability that the null hypothesis will fail to be rejected when it is false. In Scenario A, the beneficiary of a well-designed survey is the site, since a clean site will be more likely to be found to be clean. It thus behooves the site operator to perform a good survey. However, in Scenario B, the beneficiary of a good survey is the regulator. Thus, it behooves the regulator to carefully monitor the design and execution of the survey to minimize the probability that a site containing residual radioactive material is incorrectly released.

After completion of the survey, the actual values of the parameters that determine the power of the test will be known with greater certainty. For Scenario B, retrospective power analysis (**Appendix M**) is then required to ensure that the survey had adequate power. From a regulatory standpoint, there are concerns that an inadequate survey could lead to false adoption of the null hypothesis under Scenario B and, consequently, the release of survey units with inadequate remediation.

D.1.6 Specify Performance or Acceptance Criteria

Decisions based on survey results can often be reduced to a choice between “yes” and “no,” such as determining whether a survey unit meets the release criteria. When viewed in this way, two types of incorrect decisions, or decision errors, are identified: (1) incorrectly deciding that the answer is “yes” when the true answer is “no,” and (2) incorrectly deciding the answer is “no” when the true answer is “yes.” The distinctions between these two types of errors are important for two reasons: (1) the consequences of making one type of error versus the other may be very different, and (2) the methods for controlling these errors are different and involve tradeoffs. For these reasons, the decision-maker should specify levels for each type of decision error.

The purpose of this section is to specify the decision-maker’s limits on decision errors, which are used to establish performance goals for the data collection design. The goal of the planning team is to develop a survey design that reduces the chance of making a decision error.

Although the possibility of a decision error can never be totally eliminated, it can be controlled. To control the possibility of making decision errors, the planning team attempts to control uncertainty in the survey results caused by sampling design error and measurement uncertainty. Sampling design error may be controlled by increasing the number of samples. Using more precise measurement techniques or field duplicate analyses can reduce measurement uncertainty. Better sampling designs can also be developed to collect data that more accurately and efficiently represent the parameter of interest. Every survey will use a slightly different method of controlling decision errors, depending on the largest source of error and the ease of reducing those error components. The estimate of the standard deviation for the measurements performed in a survey unit (σ_s) includes the individual measurement uncertainty and the spatial and temporal variations captured by the survey design, as shown in **Equation D-1:**

$$\sigma_s^2 = \sigma_{spatial}^2 + \sigma_{measurement}^2 \qquad \textbf{Equation D-1}$$

Although individual measurement uncertainties are not used during the FSS data assessment, establishing acceptable measurement uncertainty limits on results will be a factor in choosing appropriate measurement systems for the expected residual radioactive materials of concern. Additionally, individual measurement uncertainties may be useful for determining an a priori estimate of σ_s during survey planning. Because a larger value of σ_s results in an increased number of measurements needed to demonstrate compliance during the FSS, the decision-maker may seek to reduce measurement uncertainty through various methods (e.g., different instrumentation). Spatial uncertainty can be reduced by defining survey units that are more homogeneous (with respect to likely residual radioactivity).

There are tradeoffs that should be considered during survey planning. For example, the costs associated with performing additional measurements with an inexpensive measurement system may be less than the costs associated with a measurement system with better sensitivity (i.e., lower measurement uncertainty, lower minimum detectable concentration [MDC]). However, the more expensive measurement system with better sensitivity may reduce σ_s and the number of measurements used to demonstrate compliance, to the point at which it is more cost effective to use the more expensive measurement system. For surveys in the early stages of the RSSI process, the instrument uncertainty and instrument detection capability become even more important. During scoping, characterization, and remedial action support surveys, decisions about classification and remediation are made based on a limited number of measurements. When the instrument detection capability value approaches the value of the DCGL or AL, it becomes more difficult to make these decisions. From an operational standpoint, when operators of a measurement system have an a priori understanding of the detection capability and potential measurement uncertainties, they can recognize and respond to conditions that may warrant further investigation (e.g., changes in background radiation levels, the presence of areas of elevated activity, measurement system failure or degradation).

The probability of making decision errors can be controlled by adopting a scientific approach called hypothesis testing. In this approach, the survey results are used to select between one condition of the environment (the null hypothesis, H_0) and an alternative condition (the alternative hypothesis, H_1). The null hypothesis is treated like a baseline condition that is assumed to be true in the absence of strong evidence to the contrary. Acceptance or rejection of the null hypothesis depends upon whether the particular survey results are consistent with the hypothesis. A decision error occurs when the decision-maker rejects the null hypothesis when it is true or accepts the null hypothesis when it is false. These two types of decision errors are classified as Type I and Type II decision errors and can be represented as shown in **Table D-1** for Scenario A and **Table D-2** for Scenario B.

A Type I decision error occurs when the null hypothesis is rejected when it is actually true; it is sometimes referred to as a false positive error. The probability of making a Type I decision error, or the level of significance, is denoted by alpha (α). Alpha reflects the amount of evidence the decision-maker would like to see before abandoning the null hypothesis; this is also referred to as the size of the test.

A Type II decision error occurs when the null hypothesis is accepted when it is actually false. This is sometimes referred to as a false negative error. The probability of making a Type II decision error is denoted by beta (β). The term ($1-\beta$) is the probability of correctly rejecting the null hypothesis; this is also referred to as the power of the test.

Table D-1 Representation of Decision Errors for an FSS Using Scenario A[a] for the True Condition of the Survey Unit

If the True Condition of the Survey Unit Is…	…and Based on the FSS, the Decision Is Made to…	
	Reject H_0	**Accept H_0**
Meets Release Criteria	There is no decision error.	There is a Type II decision error (β): Incorrectly Fail to Release Survey Unit.
Exceeds Release Criteria	There is a Type I decision error (α): Incorrectly Release Survey Unit.	There is no decision error.

[a] In Scenario A, H_0 is that the residual activity in the survey unit exceeds the release criteria.

Table D-2 Representation of Decision Errors for an FSS Using Scenario B[a] for the True Condition of the Survey Unit

If the True Condition of the Survey Unit Is…	…and Based on the FSS, the Decision Is Made to…	
	Reject H_0	**Accept H_0**
Exceeds Release Criteria	There is no decision error.	There is a Type II decision error (β): Incorrectly Release Survey Unit.
Meets Release Criteria	There is a Type I decision error (α): Incorrectly Fail to Release Survey Unit.	There is no decision error.

[a] In Scenario B, H_0 is that the residual activity in the survey unit does not exceed the release criteria.

As shown in **Table D-2,** the definitions of Type I and Type II error for Scenario A are reversed in Scenario B. The Type I error rate is controlled by lowering α. In Scenario A, a lower value of α reduces the probability of incorrectly releasing a survey unit that exceeds the release criteria. In Scenario B, a lower value of α reduces the probability of failing to release a survey unit that does not exceed the release criteria. A similar reversal of meaning exists for β. In Scenario A, a lower value of β reduces the probability of failing to release a survey unit that does not exceed the release criteria. In Scenario B, a lower value of β reduces the probability of incorrectly releasing a survey unit that exceeds the release criteria.

There is a relationship between α and β that is used in developing a survey design. In general, increasing α decreases β, and vice versa, holding all other variables constant. Increasing the number of measurements typically results in a decrease in both α and β. The number of measurements that will produce the desired values of α and β from the statistical test can be estimated from α, β, the $DCGL_W$ or AL, the LBGR or DL, and the estimated standard deviation of the distribution of the parameter of interest.

Five activities are associated with specifying limits on decision errors:

(1) Determine the possible range of the parameter of interest. Establish the range by estimating the likely upper and lower bounds based on professional judgment.

(2) Identify the decision errors and choose the null hypothesis.

- Define both types of decision error (Type I and Type II).
- Specify and evaluate the potential consequences of each decision error.
- Establish which decision error has more severe consequences near the AL. Consequences may include health, ecological, political, social, and resource risks.
- Define the null hypothesis and the alternative hypothesis, and assign the terms "Type I" and "Type II" to the appropriate decision error.

(3) Specify a range of possible parameter values, also known as a "gray region," where the consequences of decision errors are relatively minor. It is necessary to specify a gray region because variability in the parameter of interest and unavoidable uncertainty in the measurement method combine to produce variability in the data such that a decision may be "too close to call" when the true but unknown value of the parameter of interest is very near the AL. Additional guidance on specifying a gray region is available in EPA QA/G-4. In Scenario A, the UBGR is the $DCGL_W$, and the LBGR is a value that represents a conservative estimate of the amount of radioactive material existing in the survey unit. In Scenario B, the LBGR is the AL, and the UBGR is the DL, a value chosen during the planning process that provides an indication of survey effort.

(4) Assign probability limits to points above and below the gray region that reflect the probability for the occurrence of decision errors.

(5) Graphically represent the decision rule with a prospective power curve (**Appendix M**).

The expected outputs of this step are decision error rates based on the consequences of making an incorrect decision. Certain aspects of the site investigation process, such as the HSA, are not so quantitative that numerical values for decision errors can be specified. Nevertheless, a "comfort region" should be identified where the consequences of decision errors are relatively minor.

D.1.6.1 Determine the Possible Range of the Parameter of Interest

Section D.1.5 defines the parameter of interest as the mean concentration of residual radioactive material, specifically, the difference between the survey unit mean concentration of residual radioactive material and the reference area mean concentration if the radionuclide is present in background, or simply the survey unit mean concentration if the radionuclide is not present in background. The possible range of values for the parameter of interest is determined based on existing information (such as the HSA or previous surveys) and best professional judgment. For an FSS, wherein the residual radioactive material is expected to meet the release criteria, a conservative upper bound might be approximately three times the $DCGL_W$; the likely lower bound is either background (if the radionuclide associated with the residual radioactive material is found in the reference area) or at zero (if the radionuclide is not found in the reference area).

D.1.6.2 Identifying the Decision Errors and Choosing the Null Hypothesis

Hypothesis testing is used to determine whether a statement concerning the parameter of interest should be verified. The statement about the parameter of interest is called the null hypothesis. The alternative hypothesis is the opposite of what is stated in the null hypothesis.

The decision-maker needs to choose between two courses of action, one associated with the null hypothesis and one associated with the alternative hypothesis.

To make a decision using hypothesis testing, a test statistic[3] is compared to a critical value. The test statistic (s) is a number calculated using data from the survey. The critical value of the test statistic defines a rejection region based on some assumptions about the true distribution of data in the survey unit. If the value of the test statistic falls within the rejection region, the null hypothesis is rejected. The decision rule, developed in **Section D.1.5**, is used to describe the relationship between the test statistic and the critical value.

MARSSIM considers two ways to state H_0 for an FSS. The primary consideration in most situations will be compliance with the release criteria.

For Scenario A, the null hypothesis is that the survey unit exceeds the release criteria. A Type I decision error would result in the release of a survey unit containing residual radioactive material above the release criteria. The probability of making this error is α. This requires significant evidence that the residual radioactivity in the survey unit is less than the release criteria to reject the null hypothesis (and pass the survey unit). If the evidence is not significant at level α, the null hypothesis of a noncomplying survey unit is accepted (and the survey unit fails). Setting a high value for α would result in a higher risk that survey units that might be somewhat in excess of the release criteria would be passed as meeting the release criteria. Setting a low value for α would result in fewer survey units for which the null hypothesis is rejected. However, the cost of setting a low value for α is either a higher value for β or an increased number of samples used to demonstrate compliance.

The mean shift for the survey unit must be significantly below the release criteria for the null hypothesis to be rejected. With this test, site owners face a tradeoff between additional sampling costs and unnecessary remediation costs. For survey units at or near background levels, they may choose to increase the number of measurements in order to decrease the number of Type II decision errors (reduce the chance of remediating a clean survey unit).

Distinguishability from background is not addressed directly. However, sample sizes may be selected to provide adequate power at or near background levels, ensuring that most survey units near background would pass. Additional analyses, such as point estimates or confidence intervals, or both, may be used to address this question.

A high percentage of survey units slightly below the release criteria may fail the release criteria, unless large numbers of measurements are used. This achieves a high degree of assurance that most survey units that are at or above the release criteria will not be improperly released.

For Scenario B, the null hypothesis is that the survey unit meets the release criteria (i.e., the survey unit is indistinguishable from background). A Type I decision error would result in failing to release a survey unit that does not contain residual radioactive material above the release criteria. The probability of making this error is α. This requires significant evidence that the survey unit residual radioactivity is greater than background to reject the null hypothesis (and fail the survey unit). If the evidence is not significant at level α, the null hypothesis of a clean survey unit is accepted (and the survey unit passes). Setting a high value for α would result in a higher likelihood that survey units might be somewhat below the release criteria and still fail to

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[3] The test statistic is not necessarily identical to the parameter of interest but rather is functionally related to it through the statistical analysis.

meet the release criteria. Setting a low value for α would result in fewer survey units where the null hypothesis is rejected. Here again, the cost of setting a low value for α is either a higher value for β or an increased number of samples used to demonstrate compliance.

The residual radioactivity in the survey unit must be significantly above background for the null hypothesis to be rejected. However, if residual radioactivity levels are slightly below the release criteria, a high percentage of survey units will fail unless the number of measurements is increased. This is necessary to achieve a high degree of assurance that most sites at or above the release criteria in the null hypothesis will fail to be improperly released.

Compliance with the DCGLs is not addressed directly. However, the number of measurements may be selected to provide adequate power at or near the DCGL, ensuring that most survey units near the DCGL would not be improperly released. Additional analysis, based on point estimates or confidence intervals, or both, is required to determine compliance if the null hypothesis is rejected by the test.

More information on Scenario B can be found in the NRC draft report NUREG-1505, Revision 1, "A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys: Interim Draft Report for Use and Comment," issued June 1998 (NRC 1998a).

For Scenario A, the alternative hypothesis is that the survey unit does meet the release criteria. A Type II decision error would result in either unnecessary costs due to remediation of survey units that are truly below the release criteria or additional survey activities to demonstrate compliance. The probability of making a Type II error is β. Selecting a high value for β (low power) would result in a higher risk that survey units that actually meet the release criteria are subject to further investigation. Selecting a low value for β (high power) will minimize these investigations, but the tradeoff is either a higher value for α or an increased number of measurements used to demonstrate compliance.

For Scenario B, the alternative hypothesis is that the survey unit does not meet the release criteria. A Type II decision error would result in releasing a survey unit that has residual radioactive material above the release criteria. The probability of making a Type II error is β. Selecting a high value for β (low power) would result in a higher risk that survey units that do not meet the release criteria are released. Selecting a low value for β (high power) will minimize the risk of releasing survey units with residual radioactive material above the release criteria, but the tradeoff is either a higher value for α or an increased number of measurements used to demonstrate compliance.

Setting acceptable values for α and β is a crucial step in the DQO process. One consideration in setting the false positive rate is the health risks associated with releasing a survey unit that might actually contain residual radioactive material in excess of the $DCGL_W$. If a survey unit did exceed the $DCGL_W$, the first question that arises is, "How much above the $DCGL_W$ is the residual radioactive material likely to be?" Therefore, it is important to examine the probability of deciding that the survey unit does not meet the release criteria over the entire range of possible residual radioactive material values, and not only at the boundaries of the gray region.

As stated previously, the values of α and β that are selected in the DQO process should reflect the risk involved in making a decision error. In setting values for α in Scenario A and β in Scenario B, the following are important considerations:

- In radiation protection practice, public health risk is modeled as a linear function of dose (BEIR 1990). Therefore, a 10 percent change in dose, such as from 15 to 16.5, results in a 10 percent change in risk. This situation is quite different from one in which there is a threshold. In the latter case, the risk associated with a decision error can be quite high, and low values of α should be selected. When the risk is linear, much higher values of the decision error at the release criteria might be considered adequately protective when the survey design results in smaller decision error rates at doses or risks greater than the release criteria.

- The conservatism of the analysis used to develop DCGLs could be considered in setting the value of the decision error that could support the use of larger values in some situations (e.g., when screening-level DCGLs are expected to significantly overpredict dose). In these cases, as part of the DQO process, one would prospectively address the magnitude, significance, and potential consequences of decision errors at values above the release criteria. The assumptions made in any model used to predict DCGLs for a site should be examined carefully to determine whether (1) the use of site-specific parameters results in large changes in the DCGLs or (2) a site-specific model should be developed, rather than designing a survey around DCGLs that may be too conservative. The risk of making the second type of decision error in Scenario A (β) is the risk of requiring additional remediation when a survey unit already meets the release criteria. For Scenario B, β is the risk of releasing a survey unit when additional remediation may be needed to meet the release criteria.

- Unlike the health risk, the cost associated with this Type II error may be highly nonlinear. The costs will depend on whether the survey unit has already undergone remediation work and on the type of residual radioactive material present. There may be a threshold below which the remediation cost rises very rapidly. If so, a low value for the decision error is appropriate at that threshold value. This is primarily an issue for survey units that have a substantial likelihood of falling at or above the gray region for residual radioactive material. For survey units that are very lightly affected by residual radioactive material or have been so thoroughly remediated that any residual radioactive material is expected to be far below the DCGL, larger values of decision error may be appropriate, especially if FSS sampling costs are a concern. Again, it is important to examine the probability of deciding that the survey unit does not meet the release criteria over the entire range of possible residual radioactive material values, both below and above the gray region.

- Lower decision error rates may be possible if alternative sampling and analysis techniques can be used that result in higher precision (lower uncertainty). The same might be achieved with moderate increases in sample sizes. These alternatives should be explored before accepting higher design error rates. However, in some circumstances—such as high background variations, lack of a radionuclide-specific technique, or radionuclides that are very difficult and expensive to quantify—error rates that are lower than the uncertainties in the dose or risk estimates may be neither cost effective nor necessary for adequate radiation protection.

D.1.6.3 Specifying the Gray Region

Under Scenario A, the gray region is always bounded from above by the DCGL corresponding to the release criteria. The LBGR is selected during the DQO process to represent a conservative estimate of the remaining radioactive material in the survey unit. The width of the

gray region under Scenario A, equal to (DCGL – LBGR), is a parameter that is central to the nonparametric tests discussed in this manual.

Under Scenario B, the UBGR is the DL, which provides an indication of the amount of survey effort needed, and the AL, defined as the release criteria, is the LBGR. The width of the gray region is equal to (DL – AL).

Under both scenarios, this width of the gray region is also referred to as the shift, Δ. The absolute size of the shift is less important than the relative shift (Δ/σ), where σ is an estimate of the standard deviation of the measured values in the survey unit, and Δ is the width of the gray region. The estimated standard deviation includes both the real spatial variability in the quantity being measured and the uncertainty of the chosen measurement method. The relative shift is an expression of the resolution of the measurements in units of measurement uncertainty. Expressed in this way, it is easy to see that relative shifts of less than one standard deviation, $\Delta/\sigma < 1$, will be difficult to detect. On the other hand, relative shifts of more than three standard deviations, $\Delta/\sigma > 3$, are generally easier to detect. The number of measurements that will be required to achieve given error rates, α and β, depends almost entirely on the value of the relative shift (**Chapter 5**).

Because small values for the relative shift result in large numbers of samples, it is important to design a MARSSIM survey such that $\Delta/\sigma > 1$ whenever possible. There are two obvious ways to increase the relative shift. The first is to increase the width of the gray region by making the LBGR smaller or the DL larger. In the former, this means decreasing the residual radioactive material in the survey unit, and in the latter, this means decreasing the amount of survey effort invested in distinguishing 0 from some amount of radioactive material. Only Type II decision errors occur in the gray region, so increasing the gray region increases the region where Type II decision errors can occur. In Scenario A, this means there is a greater chance of not releasing a survey unit that is below the DCGL, and in Scenario B, this means there is a greater chance of inadvertently releasing a survey unit above the AL.

The second way to increase Δ/σ is to make σ smaller; one way to make σ small is to use survey units that are relatively homogeneous in the amount of measured radioactive material. This is an important consideration in selecting survey units that have both relatively uniform levels of residual radioactive material and relatively uniform background radiation levels. Another way to make σ small is to use more precise measurement methods (measurement methods with less uncertainty). The more precise methods might be more expensive, but this may be compensated for by the decrease in the number of required measurements. The use of less precise measurements in a Scenario B environment is not advisable, due to the detection capabilities and data accuracy and precision necessary to demonstrate whether significant variability in background exists and then that the survey unit concentrations cannot be distinguished from background.

The planning team determines from the DQO outputs the minimum number of direct measurements or samples required to assess a survey unit and whether compliance with the release criteria can be satisfied. Compliance demonstration is based on certain statistical tests and the associated project and regulatory-accepted decision errors (**Section 5.3.4**). Part of the DQO process also includes an evaluation of, and selection from, the available measurement methods for the sample matrices to be collected. Measurements or samples used in the compliance decision are typically analyzed with a very high precision (or low uncertainty). However, high-precision data may be cost or schedule prohibitive even when fewer samples

may be required to demonstrate compliance. The planning team could then consider a less precise measurement or analytical technique.

The less precise methods may initially be less expensive upfront but can result in the need for a larger sample population due to inherent additional measurement uncertainty. The additional measurement uncertainty would be reflected in a higher estimated sample population variability (σ), thereby increasing the required sample size to maintain the desired statistical power.

The converse may also be true, whereby more precise measurements may reduce project costs with fewer samples yet still optimize the statistical power of the sample plan. Consider an example in which thorium-230 (^{230}Th) is the radionuclide of concern. The planning team must decide whether the data for soil samples analyzed for ^{230}Th during characterization with the less precise method of gamma spectroscopy counting should be used to provide the estimates of survey unit mean and uncertainty for FSS planning. The low-energy and low-abundance gamma emission from ^{230}Th can result in gamma spectroscopy concentrations with large relative uncertainties. This uncertainty will be reflected in the estimate of the mean used as the LBGR in Scenario A, and overall uncertainty will be reflected in the σ, both of which are used in the relative shift calculation to estimate the number of samples necessary to demonstrate compliance with the regulatory criteria. The uncertainty may then be further compounded if the sample counting times are not long enough. Factors inherent to the sample itself—such as sample self-attenuation, low sample volume, and moisture—may also affect analytical efficiency or introduce systematic bias that should be identified and addressed. The planning team may evaluate various options. The first option may be reanalyzing the characterization samples, perhaps by increasing the gamma spectroscopy sample counting time to reduce both the MDC and the measurement uncertainty. Alternatively, the user may evaluate the costs associated with analyzing the FSS samples by the more precise method of radiochemistry separation and alpha spectroscopy counting. Alpha spectroscopy analysis may be more beneficial, as it provides a better estimate of the mean and reduced overall uncertainty compared to use of gamma spectroscopy.

When considering the less precise measurement technique, the user must first establish that the MQOs will be satisfied. The user must also be aware that the less precise measurement techniques may introduce additional analytical uncertainty to the estimate of the mean, as discussed earlier in this section, and require a larger sample population. A larger sample population may provide a better estimation of the mean concentration when extensive spatial variability of the radioactive material exists or is suspected within the survey unit. The threshold at which an increased sample population will counteract the increased measurement uncertainty and maintain the desired (prospective) statistical power will vary from survey unit to survey unit. What is critical for the planning team to recognize is that if less precise measurements are planned for the FSS and subsequently used in the DQA, then the increased relative uncertainty of the measurement process must be accounted for during the planning stage to prevent loss of statistical power. **Appendix E** provides three examples that illustrate the differences that might be expected between the prospective and DQA (retrospective) power for making a correct decision at a given mean concentration.

In summary, the greater uncertainty of the mean (larger σ) that may result from the combination of large spatial variability and a less precise (higher uncertainty) measurement system must be accounted for during planning; otherwise, sufficient samples may not be collected to maintain statistical power. This will be particularly important if precise measurement data are used to establish the relative shift value and less precise data are generated during the FSS for the data assessment phase of the data life cycle. The planning team should fully evaluate the

prospective data planning and retrospective data assessment impacts on decision-making when using less precise methods. There will be a point at which the impact of the uncertainty from less precise measurements will be negated as *N*/2 or *N* increases. Various scenario calculations may be required to predict at what point the increase in the sample population makes up for the greater uncertainty inherent in less precise measurements.

One example would be using a radionuclide-specific method rather than gross radioactive material measurements for residual radioactive material that does not appear in background. This would eliminate the variability in background from σ and would also eliminate the need for reference area measurements.

Generally, the design goal should be to achieve a Δ/σ value greater than 1. The number of samples needed rises dramatically when Δ/σ is smaller than 1. Little is usually gained by making Δ/σ larger than about 3. It is important, however, to avoid overly optimistic estimates for σ. The consequence of taking fewer samples than are needed given the actual measurement variability will be increased Type II decision errors, resulting in unnecessary remediation under Scenario A and inadvertent release of survey units that do not meet the release criteria under Scenario B.

None of the above discussion is meant to suggest that a less than rigorous, thorough, and professional approach to FSSs would be satisfactory under any circumstances. The decisions made and the rationale for making these decisions should be thoroughly documented.

For Class 1 survey units, the number of samples may be driven more by the need to detect small areas of elevated activity than by the requirements of the statistical tests. This, in turn, will depend primarily on the detection capability of available scanning instrumentation, the size of the area of elevated activity, and the dose or risk model. A given amount of residual radioactive material spread over a smaller area will, in general, result in a smaller dose or risk. However, the size of the area should not be smaller than the measurement system's capability to distinguish between area concentrations and a point source (**Section 4.6**).

The DCGL used for the elevated measurement comparison (EMC) ($DCGL_{EMC}$) is usually larger than the $DCGL_W$ used for the statistical test. In some cases, especially for radionuclides that deliver dose or risk primarily through internal pathways, dose or risk is approximately proportional to inventory, and so the difference in the DCGLs is approximately proportional to the areas. However, this may not be the case for radionuclides that deliver a significant portion of the dose or risk through external exposure. The exact relationship between the $DCGL_{EMC}$ and the $DCGL_W$ is a complicated function of the dose or risk modeling pathways (refer to **Chapter 5**).

D.1.6.4 Assigning Probability Limits to Points Above and Below the Gray Region

For many radionuclides, scanning instrumentation is readily available that has sufficient detection capability to detect residual radioactive material concentrations at the $DCGL_{EMC}$ derived for the sampling grid of direct measurements or samples used in the statistical tests. If instrumentation with sufficient detection capability is not available, the number of samples in the survey unit can be increased until the area between sampling points is small enough that $DCGL_{EMC}$ can be detected by scanning. **Chapter 5** discusses the details of this process. For some radionuclides (e.g., tritium [hydrogen-3]), the scanning detection capability is typically so low that this process would never terminate (i.e., the number of samples required could increase without limit). Thus, an important part of the DQO process is to determine the smallest size of

an area of elevated activity that it is important to detect, A_{min}, and an acceptable level of risk, R_A, that it may go undetected. **Figure D-3** shows the probability of taking a sample within a circular area of size A with either a square or triangular sampling pattern. Both Visual Sample Plan (VSP) (Matzke et al. 2014) and Spatial Analysis and Decision Assistance (SADA) (Stewart et al. 2009) can also be used to calculate these probabilities.

This part of the DQO process is concerned less with areas of elevated activity that are found than with providing adequate assurance that negative scanning results truly demonstrate the absence of such areas. In selecting acceptable values for A_{min} and R_A, maximum use of information from the HSA and all surveys before the FSSs should be used to determine what sort of areas of elevated activity could possibly exist, their potential size and shape, and how likely they are to exist. When the detection capability of the scanning technique is very poor relative to the $DCGL_{EMC}$, the number of measurements estimated to demonstrate compliance using the statistical tests may become unreasonably large. In this situation, the survey objectives and considerations can be evaluated. These considerations may include the survey design and measurement methodology, exposure pathway modeling assumptions and parameter values used to determine the DCGLs, HSA conclusions about source terms and radionuclide distributions, and the results of scoping and characterization surveys. In most cases, the results of this evaluation are not expected to justify an unreasonably large number of measurements. Composite sampling (**Section 2.6.2.2**) can be used to lower the cost of sample analyses, but it will cause the investigation level to decline to $(DCGL_{EMC})/N$, where N is the number of increments in the composite. Investigators should consult with the regulator before using composite sampling at their site.

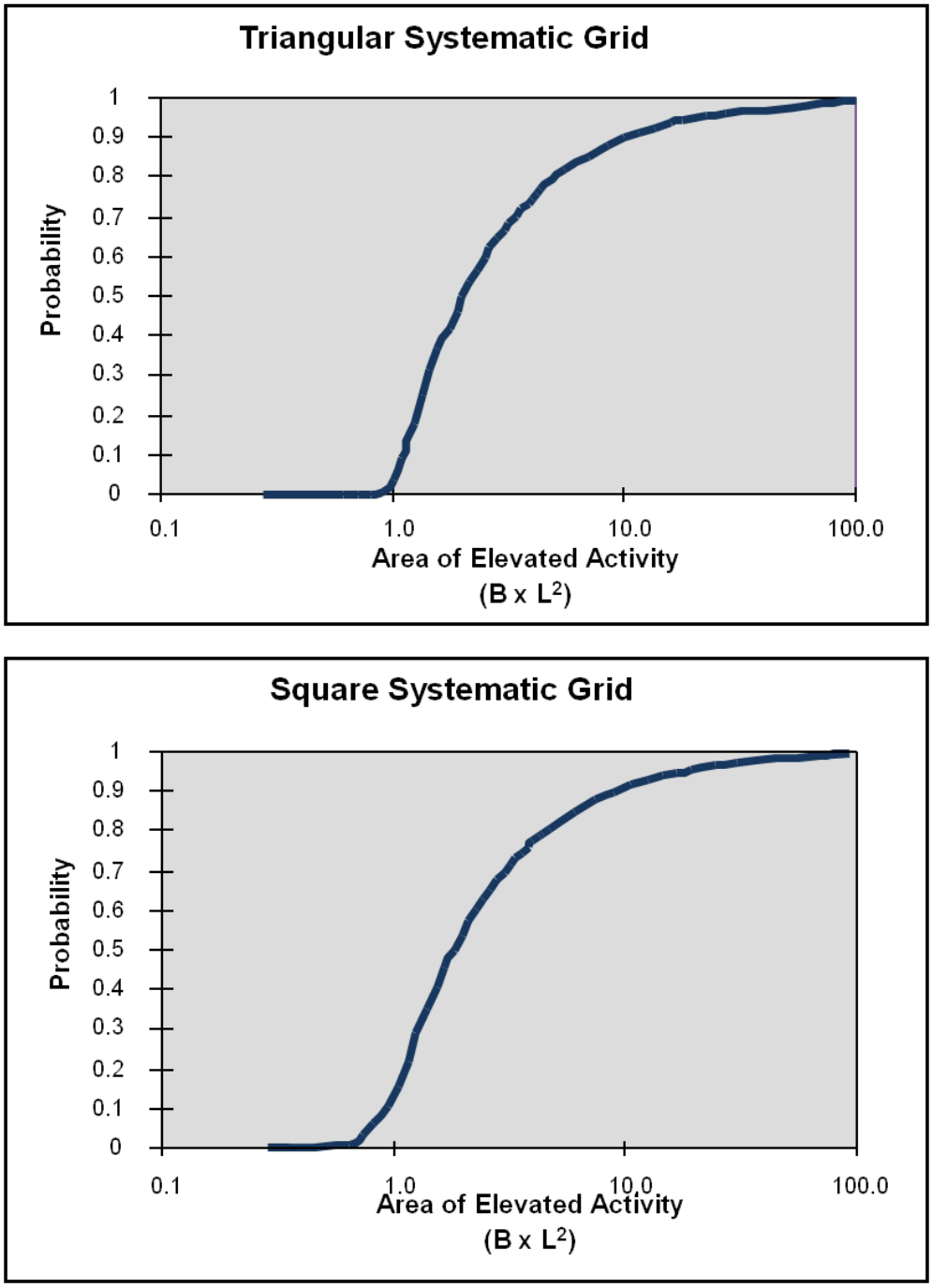

Figure D-3 Geometric Probability of Sampling at Least One Point of an Area of Elevated Activity as a Function of Sample Density with Either a Triangular or Rectangular/Square Sampling Pattern

D.1.6.5 Graphically Representing the Decision Rule

A convenient method for visualizing the decision rule is to graph the probability of deciding that the survey unit meets the release criteria. **Figure D-4** shows an example of such a chart,

referred to as a power chart. In this example, α is 0.025 and β is 0.05, providing an expected power (1−β) of 0.95 for the test.

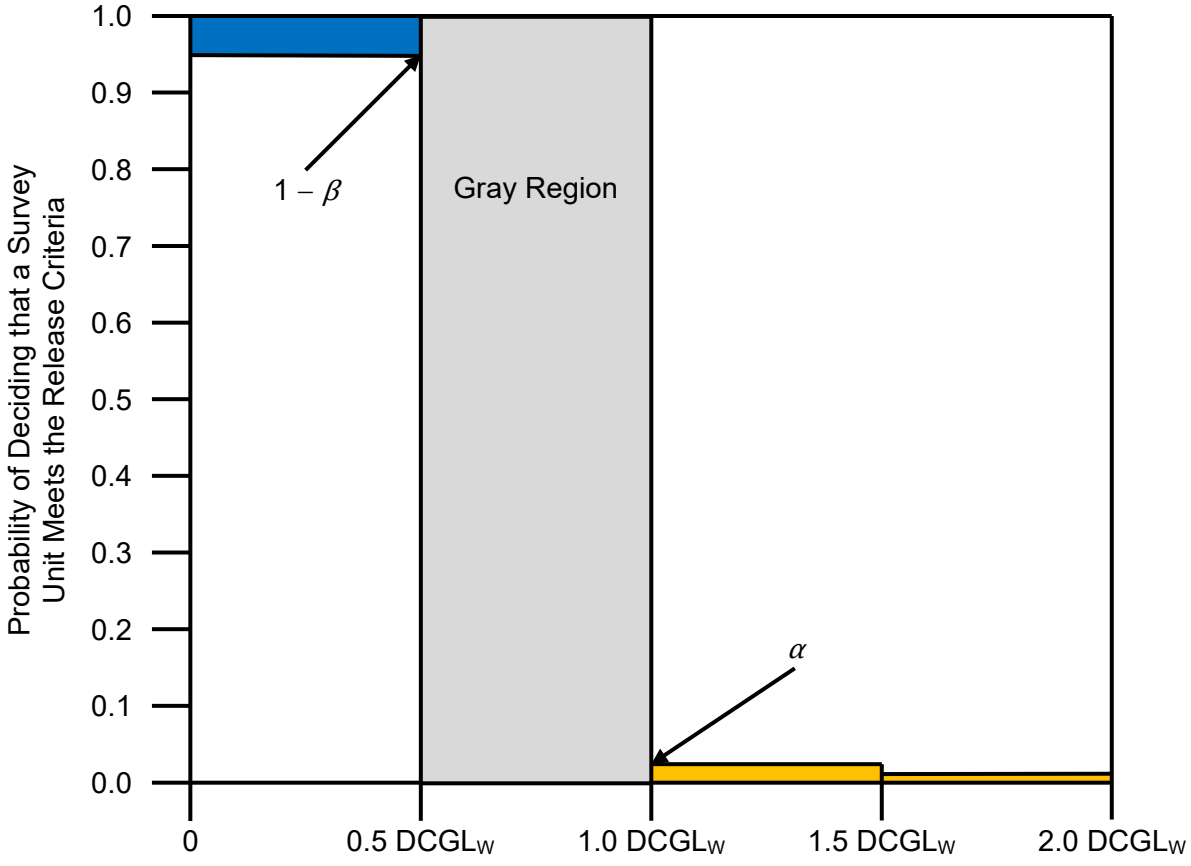

Figure D-4 Example of a Scenario A Power Chart Illustrating the Decision Rule for the FSS

Figure D-5 shows a second method for presenting the information. This figure, referred to as an error chart for Scenario A, shows the probability of making a decision error for possible values of the parameter of interest. Both examples show a gray region where the consequences of decision errors are deemed to be relatively minor. These charts are used in the final step of the DQO process, combined with the outputs from the previous steps, to produce an efficient and cost-effective survey design. Setting acceptable values for α and β, as well as determining an appropriate gray region, is a crucial step in the DQO process. **Appendix M** provides instructions for creating a prospective power curve, which can also be used to visualize the decision rule.

After the survey design is implemented, the expected values of α and β determined in this step are compared to the actual significance level and power of the statistical test based on the measurement results during the assessment phase of the data life cycle. This comparison is used to verify that the objectives of the survey have been achieved. It is recommended that several different values for α and β be investigated before specific values are selected.

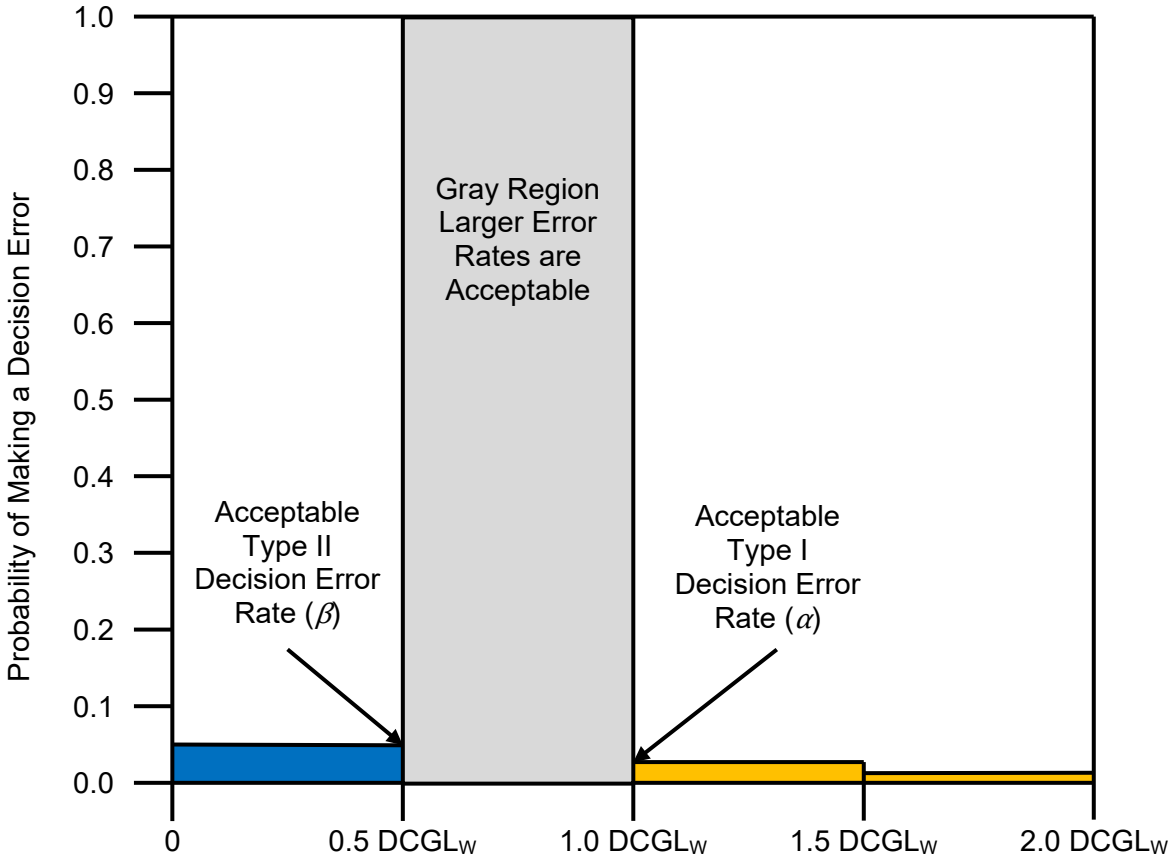

Figure D-5 Example of a Scenario A Error Chart Illustrating the Decision Rule for the FSS

D.1.7 Develop the Detailed Plan for Obtaining Data

D.1.7.1 Steps for Plan Development

This step is designed to produce a resource-effective survey design that is expected to meet the DQOs. It may be necessary to work through this step more than once after revisiting previous steps in the DQO process.

This step includes the following six activities:

(1) Review the DQO outputs and existing environmental data to ensure they are internally consistent.

(2) Develop general data collection design alternatives. **Chapter 5** describes random and systematic sampling designs recommended for FSSs based on survey unit classification.

(3) Formulate the mathematical expressions needed to solve the design problem for each data collection design alternative.

(4) Select the most resource-effective design that satisfies the DQOs for each data collection design alternative. If the recommended design will not meet the limits on decision errors within the budget or other constraints, then the planning team will need to relax one or more constraints, as in the following examples:

- Increase the budget for sampling and analysis.
- Use exposure pathway modeling to develop site-specific DCGLs.
- Increase the decision error rates, not forgetting to consider the risks associated with making an incorrect decision.
- For Scenario A, increase the width of the gray region by performing more remediation, which decreases the LBGR.
- For Scenario B, increase the width of the gray region by increasing the DL and relaxing other project constraints (e.g., schedule).
- Change the boundaries, such as by changing or eliminating survey units that will require different decisions.
- Evaluate alternative measurement techniques with lower detection limits or lower survey costs.
- Consider the use of passive controls when releasing the survey unit rather than unrestricted release.

(5) Select a resource-effective survey design that satisfies all the DQOs. Generally, the survey designs described in **Chapter 5** will be acceptable for demonstrating compliance. Atypical sites (e.g., mixed-waste sites) may require the planning team to consider alternative survey designs on a site-specific basis.

(6) Document the operational details and theoretical assumptions of the selected design in the QAPP, the field sampling plan, the sampling and analysis plan, or the decommissioning plan. All decisions that will be made based on the data collected during the survey should be specified, along with the alternative actions that may be adopted based on the survey results.

Chapters 4 and **5** present a framework for an FSS design. When this framework is combined with the site-specific DQOs developed using the guidance in this appendix, the survey design should be acceptable for most sites. The following are the key inputs to **Chapters 4** and **5:**

- investigation levels and DCGLs or ALs for each radionuclide of interest
- acceptable measurement techniques for scanning, sampling, or direct measurements, including detection limits, uncertainty estimates, and estimated survey costs
- identification and classification of survey units
- an estimate of the variability in the distribution of residual radioactive material for each survey unit, and in the reference area if necessary
- the decision-maker's acceptable a priori values for decision error rates (α and β)

D.1.7.2 Measurement Quality Objectives

The following discussion of MQOs is adapted from Section 3.8 of the Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME) manual (NRC 2009). MQOs are a subset of the DQOs that address quality objectives for the selection of field and laboratory measurement systems. They provide quantitative performance or acceptance criteria for DQIs.

The identification and evaluation of provisional measurement methods is an important step in developing a disposition survey design. A measurement method is the combination of instrumentation with a measurement technique. **Chapter 6** discusses the selection of a measurement method in more detail. The availability of measurement methods and the resources required to implement specific measurement methods are important factors in selecting between different survey designs, or in reducing the number of options to be considered when developing FSS designs.

A critical element of the measurement method evaluation is to identify project MQOs. The following subsections give examples of MQOs. The identification of measurement methods is directly or indirectly related to the following:

- identification of radionuclides of concern
- location of residual radioactive material
- application of ALs
- distribution of residual radioactive material
- expected levels of residual radioactive material
- relationships between radionuclide activities
- equilibrium status of natural decay series
- background radioactive material

The Multi-Agency Radiological Laboratory Analytical Protocols (MARLAP) manual (NRC 2004) lists method performance characteristics that should be considered when establishing MQOs for a project. This list includes the following and is not intended to be exhaustive:

- the method uncertainty at a specified concentration (expressed as a standard deviation)
- the method's detection capability or measurement sensitivity (expressed as the MDC)
- the method's range, which defines the method's ability to measure the radionuclide of concern over some specified range of concentration
- the method's specificity, which refers to the ability of the method to measure the radionuclide of concern in the presence of interferences
- the method's ruggedness, which refers to the relative stability of method performance for small variations in method parameter values

Project-specific method performance characteristics should be developed as necessary and may or may not include the characteristics listed here.

When performance characteristics that affect measurability have been identified, the planning team should develop MQOs describing the project-specific objectives for potential measurement techniques. Potential measurement techniques should be evaluated against the MQOs to determine whether they can meet the objectives for measurability.

D.1.7.2.1 Measurement Method Uncertainty

MARLAP uses the term “method uncertainty” to refer to the predicted uncertainty of a measured value that would likely result from the performance of a measurement at a specified concentration, typically the AL. Reasonable values for method uncertainty can be predicted for a particular measurement technique based on typical values for specific parameters (e.g., count time, efficiency) based on known information about the site. The MQO for measurement method uncertainty is related to the width of the gray region (**Section 5.3**). The required measurement method uncertainty is directly related to the MDC (discussed in the next subsection).

Measurement method uncertainty effectively combines precision (random error) and bias (systematic error) into a single parameter whose interpretation does not depend on context. This approach assumes that all potential sources of bias present in the measurement process have been considered in the estimation of the measurement uncertainty and, if not, that any appreciable bias would only be detected after a number of measurements of QC and performance evaluation samples have been performed (**Sections 6.2 and 7.2**). MARLAP Appendix C provides examples on developing MQOs for measurement method uncertainty of laboratory measurement techniques.

D.1.7.2.2 Detection Capability

The MDC is recommended as the MQO for defining the detection capability and is an appropriate MQO when decisions as to whether residual radioactive material is present or not are to be made based on a single measurement. **Section 6.3** provides guidance on calculation of the appropriate actual MDC. MARLAP Chapter 19 and Appendix C contain additional information on calculating the MDC.

D.1.7.2.3 Range

The expected concentration range for a radionuclide of concern may be an important measurement method performance characteristic. Most radiation measurement techniques are capable of measuring over a wide range of radionuclide concentrations. However, if the expected concentration range is large, the range should be identified as an important measurement method performance characteristic, and an MQO should be developed. The MQO for the acceptable range should be a conservative estimate. This will help prevent the selection of measurement techniques that cannot accommodate the actual concentration range.

D.1.7.2.4 Specificity

Specificity is the ability of the measurement method to measure the radionuclide of concern in the presence of interferences. To determine whether specificity is an important measurement method performance characteristic, the planning team will need information on expected concentration ranges for the radionuclides of concern and other chemical and radionuclide constituents, along with chemical and physical attributes of the soil or building surfaces being investigated. The importance of specificity depends on the following:

- the chemical and physical characteristics of the media being investigated
- the chemical and physical characteristics of the residual radioactive material
- the expected concentration range for the radionuclides of concern

If potential interferences are identified (e.g., inherent radioactivity, similar radiations), an MQO should be established for specificity.

If inherent radioactivity is associated with the media being investigated, a method that measures total activity may not be acceptable. Consider concrete surfaces, which contain measurable levels of naturally occurring radioactive material and emit radiation in the form of alpha particles, beta particles, and photons. If the AL for the radionuclide of concern is close to background (e.g., within a factor of 3), gross measurement methods may not meet the survey objectives. Performing gross alpha measurements using a gas proportional detector may not provide an acceptable MDC for plutonium isotopes, while a more specific measurement method, such as alpha spectrometry following radiochemical separation, would be acceptable.

Radionuclides have similar radiations if they emit radiations of the same type (i.e., alpha, beta, and photon) with similar energies. For example, both radium-226 and uranuim-235 emit a gamma ray with energy of approximately 186 kiloelectron-volts. Gamma spectroscopy may not be able to resolve mixtures of these two radionuclides, which are both associated with naturally occurring radioactive materials. More specific methods involving ingrowth of radium-226 decay products or chemical separation before measurement can be used to accurately quantify the radionuclides.

Documented measurement methods should include information on specificity. **Table 7-2** lists examples of references providing laboratory measurement methods. NUREG-1507, Revision 1, "Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions," issued August 2020 (NRC 2020), provides generic information on field measurement techniques, but most field measurement methods are documented in proprietary standard operating procedures (SOPs). If specificity is identified as an important issue for a project, consultation with an expert in radiometrics or radiochemistry is recommended.

D.1.7.2.5 Ruggedness

For a project that involves field measurements that are performed in hostile, hazardous, or variable environments, or laboratory measurements that are complex in terms of chemical and physical characteristics, the measurement method's ruggedness may be an important method performance characteristic. Ruggedness refers to the relative stability of the measurement technique's performance when small variations in method parameter values are made. For field measurements, the changes may include temperature, humidity, or atmospheric pressure. For laboratory measurements, a change in pH or the quantity of available sample may be important. To determine whether ruggedness is an important measurement method performance characteristic, the planning team needs detailed information on the chemical and physical characteristics of the soil and building surfaces being investigated and operating parameters for the radiation instruments used by the measurement technique. Information on the chemical and physical characteristics of the measurement media is available as outputs from the HSA. Information on the operating parameters for specific instruments should be available from the instrument manufacturer. Generic information for radiation detector operating parameters may be found in consensus standards such as, but not limited to, the following:

- American National Standards Institute (ANSI) N42.12-1994, "American National Standard Calibration and Usage of Thallium-Activated Sodium Iodide Detector Systems for Assay of Radionuclides," dated January 26, 1995 (ANSI 1995)

- ANSI N42.17A-2003, "American National Standard Performance Specifications for Health Physics Instrumentation—Portable Instrumentation for Use in Normal Environmental Conditions," dated April 29, 2004 (ANSI 2004)

- ANSI N42.17C-1989, “American National Standard Performance Specifications for Health Physics Instrumentation—Portable Instrumentation for Use in Extreme Environmental Conditions,” dated March 28, 1990 (ANSI 1990)

- ANSI N42.34-2015, “American National Standard Performance Criteria for Handheld Instruments for the Detection and Identification of Radionuclides,” dated August 24, 2016 (ANSI 2016)

- Institute of Electrical and Electronics Engineers (IEEE) 309-1999/ANSI N42.3-1999, “Institute of Electrical and Electronics Engineers, Inc. Standard Test Procedures and Bases for Geiger Mueller Counters,” dated June 4, 1999 (ANSI 1999)

- ASTM International (ASTM) E1169-2002, “Standard Guide for Conducting Ruggedness Tests,” issued 2002 (ASTM 2002)

If measurement method ruggedness is determined to be an important performance characteristic, an MQO should be developed. The MQO may require performance data that demonstrate the measurement technique’s ruggedness for specified changes in select measurement method parameters. Alternatively, the MQO could list the acceptable ranges for select measurement method parameters and monitor the parameters as part of the QC program for the project. For example, sodium iodide detectors are required to perform within 15 percent of the calibrated response between 0 and 40 degrees Celsius (32 and 104 degrees Fahrenheit, respectively) (ANSI 1995). At temperatures outside this range, the FSS design may call for a work stoppage or an increase in the frequency of QC measurements.

D.2 The Implementation Phase

To assist organizations collecting and evaluating data for a particular program with the implementation of their quality systems, the UFP-QS was developed to facilitate consistent implementation of the quality system requirements in Section 5 (Part A) of ANSI/American Society for Quality (ASQ) E4, “Quality Systems for Environmental Data and Technology Programs—Requirements with Guidance for Use,” version issued in 2004 (ANSI/ASQ 2004). (ANSI/ASQ E4 was revised as “Quality Management Systems for Environmental Information and Technology Programs—Requirements with Guidance for Use” in 2014 [ANSI/ASQ 2014].) Similarly, the UFP-QAPP was developed to facilitate consistent implementation of the project-specific requirements of Section 6 (Part B) of ANSI/ASQ E4.

The RSSI process described in MARSSIM requires that all environmental data collection and use are to take place in accordance with a site-specific systematic planning process, the elements of which are outlined in the UFP-QS, and the results documented in a project-specific QAPP based on the UFP-QAPP.

The UFP-QS serves as a high-level policy document for implementing quality systems, as defined in ANSI/ASQ E4 or equivalent. It describes the systematic planning process at a conceptual level and provides the framework to ensure that essential elements are addressed.

A “graded approach” will be used in the preparation of the project-specific QAPP for the RSSI process. A graded approach is the process of establishing the project requirements and level of effort according to the intended use of the results and the degree of confidence needed in the quality of the results. In other words, the degree of documentation, level of effort, and detail will vary based on the complexity and cost of the project. Appropriate and objective consideration will be given to the significance of the environmental problems to be investigated, the

environmental decisions to be made, and the impact on human health and the environment. Documentation will consist of a concise explanation whenever the project does not need to address a specific area.

D.2.1 The Uniform Federal Policy for Quality Assurance Project Plans

The UFP-QAPP integrates all technical and quality aspects for the life cycle of the project, including planning, implementation, and assessment. The ultimate success of an environmental program or project depends on the quality of the environmental data collected and used in decision-making, and this quality depends significantly on the adequacy of the QAPP and its effective implementation. The QAPP documents how QA/QC activities are applied to an environmental data collection operation to ensure that the results obtained will satisfy the stated performance criteria.

The QAPP serves several purposes:

- As a technical planning document, it identifies the purpose of the project; defines DQOs; and outlines the sampling, analytical, and QA/QC activities that will be used to support environmental decisions.

- As an organizational document, it identifies key project personnel, thereby facilitating communication and ensuring that key project tasks are assigned.

- As an assessment and oversight planning document, it provides the criteria for the assessment of project implementation and for QA and contractor oversight.

QAPPs can be of two types:

(1) A generic QAPP is an overarching plan that describes the quality objectives and documents the comprehensive set of SOPs for sampling, analysis, QA/QC, and data review that are specific to a site or to an activity. A generic QAPP may be applicable to a single site with multiple activities or to a single activity that will be implemented at multiple sites or at multiple times. A generic program QAPP may serve as an umbrella under which project-specific tasks are conducted over an extended period.

(2) A project-specific QAPP provides a QA blueprint specific to one project or task. Project-specific QAPPs are used for projects of limited scope and time and, in general, can be considered the sampling and analysis plan or work plan for the project. A project-specific QAPP for each site or activity may be needed to supplement a generic QAPP. The QAPP for the RSSI process is project specific. **Chapter 2** provides an overview of the RSSI process.

The UFP-QAPP addresses four basic element groups: (1) project management and objectives, (2) measurement/data acquisition, (3) assessment/oversight, and (4) data review. These four basic element groups present a framework consistent with EPA CIO 2105-S-02.1, “Quality Assurance Project Plan Standard,” dated April 3, 2024 (EPA 2024), which requires the use of a systematic planning process. The sections below describe the UFP-QAPP requirements under each of the four basic element groups.

D.2.2 Project Management and Objectives

The project management and objectives element of the QAPP ensures that the project has a defined purpose by documenting the environmental problem, the environmental questions being asked, and the environmental decisions that need to be made. The elements in this part of the QAPP identify the DQOs necessary to answer those questions and support those environmental decisions. This part of the QAPP also addresses management considerations for the project, such as roles and responsibilities. Required QAPP sections under this element include the title and approval page, document format and table of contents, distribution list and project personnel sign-off sheet, project organization, project planning/problem definition, and development of DQOs and measurement performance criteria.

The main element of project planning is scoping.[4] Scoping defines the purpose and expected results of the project; the release decisions that need to be made; the DQOs necessary to achieve expected results and support environmental decisions; the scanning, direct measurement, sampling and analytical, and data review activities that will be performed; and the final products and deliverables for the project. **Section D.1** covers this scoping process in detail.

Among the scoping topics of consideration for MARSSIM are the following:

- characterizing the site or areas of the site as impacted or non-impacted
- classifying the site or survey units within the site as either Class 1, 2, or 3 areas
- establishing what radionuclides are present at the site and in reference areas
- determining whether to apply Scenario A or Scenario B
- establishing Type I and Type II error rates for the chosen scenario
- establishing the relevant statistical information such as the gray area, variability, and relative shift for each radionuclide of interest
- establishing assessment criteria, including release criteria, statistical tests, and verification and validation criteria

The QAPP should frame the reasons for conducting the project, including historical information, current site conditions, and other existing data applicable to the project. **Chapters 3** and **4** discuss the HSA and preliminary considerations for the RSSI process. **Chapter 5** and **Section D.1** address the planning and design for the radiation survey portion of the process.

After the project team has defined the environmental decisions and identified the DQOs, the data users and QA personnel can determine the measurement performance criteria expressed as MQOs that should be satisfied to support defensible decisions. MQOs should be determined for each matrix, measurement activity, concentration level, and residual radioactive material, if applicable. The criteria should relate to the DQIs, which are the parameters that indicate the qualitative and quantitative degree of quality associated with measurement data. Detailed discussions of DQIs and MQOs appear in **Section D.4.2.6** and **Section D.1.7.2**, respectively.

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[4] The use of the term “scoping” here is in reference to project planning and has a different meaning than that of a scoping survey.

Chapter 6 discusses DQOs, MQOs, and DQIs for the field measurements and field data collection methods in the RSSI process. **Chapter 7** discusses DQOs, MQOs, and DQIs for the laboratory analysis of samples.

D.2.3 Measurement and Data Acquisition

The section of the QAPP on measurement and data acquisition includes all components of the project-specific data collection system, including process design and rationale, procedures, and requirements. The QAPP must contain sufficient documentation to assure the reviewer that representative samples from the appropriate matrix will be properly and consistently collected at the appropriate locations and that preventive and corrective action plans are in place before initiation of the sampling event:

- The QAPP should include procedures, required detection limits and uncertainties, types of instrumentation, and minimum personnel requirements for the measurement systems and instrumentation used for scanning portions of the survey.

- The QAPP should include procedures, required detection limits and uncertainties, types of instrumentation, documentation requirements, and handling, tracking, and custody procedures for the measurement systems and instrumentation used for direct measurement and sample analysis portions of the survey.

- The QAPP should document the types and frequencies of QC measurements for scanning, direct measurement, and sampling adequate to assess DQIs and MQOs.

- Topics discussed in the QAPP under this section include the sampling process design and rationale and sampling procedures and requirements.

- The QAPP should describe how project data and information will be documented, tracked, and managed, from generation in the field to final use and storage, in a manner that ensures data integrity, defensibility, and retrieval. Activities that should be documented in the QAPP include project documentation and records, data package deliverables (scanning measurement data and laboratory data), data reporting formats, data logging and data handling management, and data tracking and control.

Chapters 6 and **7** discuss measurements and data acquisition in the RSSI process.

D.2.4 Assessment, Oversight, and Data Review

Assessment, oversight, and data review are the last element groups in the UFP-QAPP. Assessment and oversight ensure that planned project activities are implemented as described in the QAPP and that reports are provided to inform management of the project status and any QA issues that arise during implementation. Assessment activities help ensure that the quality of the resultant data is adequate for their intended use and that appropriate responses are in place to address nonconformances and deviations from the QAPP. Data review is the process by which individual data points and the dataset as a whole are evaluated and assessed.

Chapter 8 discusses the interpretation and assessment of survey results in the RSSI process. **Section D.4** provides guidance on verifying and validating data collected during an FSS specifically designed to demonstrate compliance with a dose- or risk-based regulation, such as the RSSI process.

D.3 The Assessment Phase

Data verification is used to ensure that the requirements stated in the planning documents are implemented as prescribed. Data validation is used to ensure that the results of the data collection activities support the objectives of the survey, as documented in the QAPP, or permit a determination that these objectives should be modified. **Figure D-6** illustrates where data verification, data validation, and DQA fit into the assessment phase. **Section D.4** provides detailed guidance on data verification and validation.

The DQA process has five steps:

(1) Review the DQOs, MQOs, and survey design.
(2) Conduct a preliminary data review.
(3) Select the statistical test.
(4) Verify the assumptions of the statistical test.
(5) Draw conclusions from the data.

These five steps are presented in a linear sequence, but the DQA process is applied in an iterative fashion much like the DQO process. The strength of the DQA process is that it is designed to promote an understanding of how well the data will meet their intended use by progressing in a logical and efficient manner.

D.3.1 Review Data Quality Objectives and Survey Design

The DQA process begins by reviewing the key outputs from the planning phase that are recorded in the planning documents (e.g., the QAPP). The DQOs provide the context for understanding the purpose of the data collection effort. They also establish qualitative and quantitative criteria for assessing the quality of the dataset for the intended use. The survey design (documented in the QAPP) provides important information about how to interpret the data.

D.3.2 Conduct a Preliminary Data Review

To learn about the structure of the data—identifying patterns, relationships, or potential anomalies—one can review QA/QC reports, prepare graphs of the data, and calculate basic statistical quantities.

Radiological survey data are usually obtained in units, such as the number of counts per unit of time, that have no intrinsic meaning relative to DCGLs. For comparison of survey data to DCGLs, the survey data from field and laboratory measurements are converted to DCGL units. **Sections 6.6.4** and **6.7** contain further information on instrument calibration and data conversion.

The following are the basic statistical quantities that should be calculated for the sample or direct measurement dataset:

- mean
- standard deviation
- median

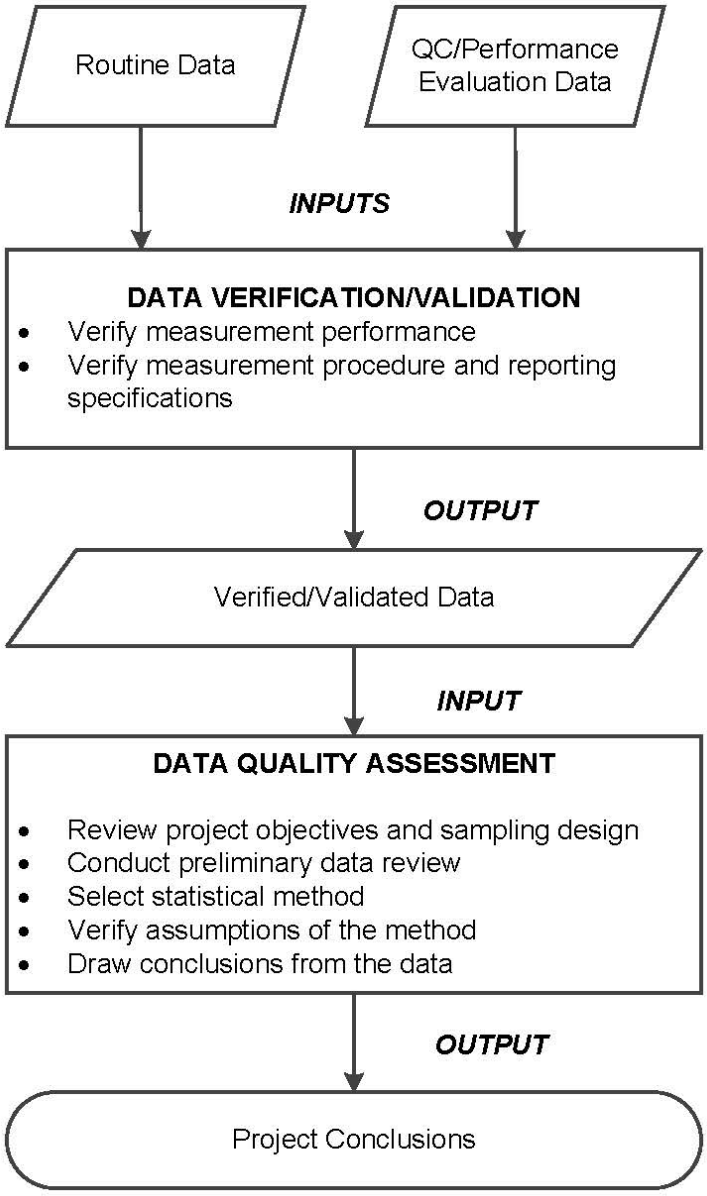

Figure D-6 The Assessment Phase

D.3.3 Select the Statistical Test

The most appropriate procedure for summarizing and typically analyzing the data is chosen based on the preliminary data review. The parameter of interest is the mean concentration in the survey unit. The nonparametric tests recommended in this manual, in their most general form, are tests of the median. If one assumes that the data are from a symmetric distribution—where the median and the mean are effectively equal—these are also tests of the mean. If the assumption of symmetry is violated, then nonparametric tests of the median approximately test the mean. Computer simulations (e.g., Hardin and Gilbert 1993) have shown that the approximation is a good one. That is, the correct decision will be made about whether the mean concentration exceeds the DCGL, even when the data come from a skewed distribution. In this

regard, the nonparametric tests are found to be correct more often than the commonly used Student's *t*-test. The robust performance of the Sign, Quantile, and WRS tests over a wide range of conditions is the reason the tests are recommended in this manual.

When a given set of assumptions is true, a parametric test designed for exactly that set of conditions will have the highest power. For example, if the data are from a normal distribution, Student's *t*-test will have higher power than the nonparametric tests. It should be noted that, for large enough sample sizes (e.g., large number of measurements), Student's *t*-test is not a great deal more powerful than the nonparametric tests. On the other hand, when the assumption of normality is violated, the nonparametric tests can be very much more powerful than the *t*-test. Therefore, any statistical test may be used, provided that the data are consistent with the assumptions underlying their use. When these assumptions are violated, the prudent approach is to use the nonparametric tests, which generally involve fewer assumptions than their parametric equivalents.

The Sign statistical test described in **Section 5.3.4** should only be used if the radionuclide is not present in background and radionuclide-specific measurements are made. The Sign test may also be used if the radionuclide is present at such a small fraction of the $DCGL_W$ value as to be considered insignificant. In this case, background concentrations of the radionuclide are included with the residual radioactive material (i.e., the entire amount is attributed to facility operations). Thus, the total concentration of the radionuclide is compared to the release criteria. This option should only be used if one expects that ignoring the background concentration will not affect the outcome of the statistical tests. The advantage of ignoring a small background contribution is that no reference area is needed. This can simplify the FSS considerably.

The Sign test (**Section 8.3.1**) evaluates whether the median of the data is above or below the $DCGL_W$. If the data distribution is symmetric, the median is equal to the mean. When the data are severely skewed, the value for the mean difference may be above the $DCGL_W$ while the median difference is below the $DCGL_W$. In such cases of severe skewness, the survey unit does not meet the release criteria, regardless of the result of the statistical tests. On the other hand, if the largest measurement is below the $DCGL_W$, the Sign test will always show that the survey unit meets the release criteria.

For FSSs, the WRS statistical test (discussed in **Sections 5.3.3** and **8.4.2**) should be used when the radionuclide of concern appears in background or if measurements are used that are not radionuclide specific. If Scenario B was selected during the DQO process, the Quantile test (**Section 8.4.3**) should also be performed. The WRS test assumes that the reference area and survey unit data distributions are similar except for a possible shift in the medians. When the data are severely skewed, the value for the mean difference may be above the $DCGL_W$ while the median difference is below the $DCGL_W$. In such cases of severe skewness (checked by the Quantile test), the survey unit does not meet the release criteria, regardless of the result of the statistical test. On the other hand, if the difference between the largest survey unit measurement and the smallest reference area measurement is less than the $DCGL_W$, the WRS test will always show that the survey unit meets the release criteria.

D.3.4 Verify the Assumptions of the Statistical Test

An evaluation to determine that the data are consistent with the underlying assumptions made for the statistical procedures helps validate the use of a test. One may also determine that certain departures from these assumptions are acceptable when given the actual data and other information about the study. The nonparametric tests described in this chapter assume that the

data from the reference area or survey unit consist of independent samples from each distribution.

Spatial dependencies that potentially affect the assumptions can be assessed using posting plots (**Section 8.2.2.2**). More sophisticated tools for determining the extent of spatial dependencies are also available (e.g., EPA 2006b). These methods tend to be complex and are best used with guidance from a professional statistician.

Asymmetry in the data can be diagnosed with a stem and leaf display, a histogram, or a Quantile test. Data transformations can sometimes be used to minimize the effects of asymmetry.

One of the primary advantages of the nonparametric tests used in this report is that they involve fewer assumptions about the data than their parametric counterparts. If parametric tests are used (e.g., Student's *t*-test), then any additional assumptions made in using them should be verified (e.g., testing for normality). These issues are discussed in detail in EPA QA/G-9S, "Data Quality Assessment: Statistical Methods for Practitioners," issued February 2006 (EPA 2006b).

One of the more important assumptions made in the survey design described in **Chapter 5** is that the sample sizes determined for the tests are sufficient to achieve the DQOs set for the Type I and Type II error rates. Verification of the power of the tests ($1-\beta$) may be of particular interest. **Appendix M** discusses methods for assessing the power. For example, in Scenario A, if the hypothesis is accepted that the survey unit residual radioactive material exceeds the release criteria, there should be reasonable assurance that the test is equally effective in determining that a survey unit has residual radioactive material less than the $DCGL_W$. Otherwise, unnecessary remediation may result.

Alternatively, in Scenario B, if the hypothesis is accepted that the survey unit residual radioactive material is less than the release criteria, there should be reasonable assurance that the test is equally effective in determining that a survey unit has residual radioactive material greater than the AL. A retrospective power analysis (**Appendix M**) at the DL is required for Scenario B survey designs to address this concern.

For both scenarios, it is better to plan the surveys cautiously—even to the point of doing the following:

- overestimating the potential data variability
- taking more samples than required for the statistical tests chosen
- making conservative assumptions in calculating the MDC, thus overestimating the value of the MDC

If one is unable to show that the DQOs were met with reasonable assurance, a re-survey may be needed. **Table 8-2** lists examples of assumptions and possible methods for their assessment.

D.3.5 Draw Conclusions from the Data

The types of measurements that can be made in a survey unit are (1) direct measurements at discrete locations, (2) samples collected at discrete locations, and (3) scans. The Sign and WRS tests are only applied to measurements made at discrete locations. Specific details for

conducting the statistical tests are given in **Sections 8.3** and **8.4.** When the data clearly show that a survey unit meets or exceeds the release criteria, the result is often obvious without performing the formal statistical analysis. **Tables 8-3 and 8-4** give examples of circumstances leading to specific conclusions based on a simple examination of the data when sampling or direct measurement options are selected.

For site-specific scanning surveys, in Scenario A, an upper confidence limit calculated from the scan data is compared to the $DCGL_W$. **Table 8-5** gives examples of circumstances leading to specific conclusions based on a simple examination of the scanning data.

In Scenario A, if a Class 2 or 3 survey is performed using samples, direct measurements, or scanning measurements and any result above the $DCGL_W$ is found, then the classification of the survey unit must be changed to Class 1 and the scan percentage increased to 100 percent.

Both the measurements at discrete locations and the scans are subject to the EMC. The result of the EMC is not conclusive as to whether the survey unit meets or exceeds the release criteria, but it is a flag or trigger for further investigation. The investigation may involve taking further measurements to determine that the area and level of the elevated residual radioactive material are such that the resulting dose or risk meets the release criteria.[5] The investigation should also provide adequate assurance, using the DQO process, that there are no other undiscovered areas of elevated residual radioactive material in the survey unit that might otherwise result in a dose or risk exceeding the release criteria. In some cases, this may lead to reclassifying all or part of a survey unit, unless the results of the investigation indicate that reclassification is not necessary. **Table 5-4** shows the investigation level appropriate for each class of survey unit and type of measurement.

D.4 Data Verification and Validation

D.4.1 Data Verification

Data verification ensures that the requirements stated in the planning documents (e.g., the QAPP) are implemented as prescribed. Data verification activities for a project should include the following:

- Deficiencies or problems that occur during implementation should be documented and reported.
- Activities performed during the implementation phase should be assessed regularly, with findings documented and reported to management for resolution.
- Corrective actions undertaken should be reviewed for adequacy and appropriateness and documented in response to the findings.

Data verification activities should be planned and documented in the survey QAPP. These assessments may include, but are not limited to, inspections, calibration and QC checks of survey instrumentation, surveillance of field or laboratory activities, technical reviews of survey plans and survey reports, performance evaluations, and audits.

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[5] Rather than, or in addition to, taking more measurements, the investigation may involve assessing the adequacy of the exposure pathway model used to obtain the DCGLs, and the consistency of the results obtained with the HSA and the scoping, characterization, and remedial action support surveys.

To ensure that conditions requiring corrective actions are identified and addressed promptly, data verification activities should be initiated as part of data collection during the implementation phase of the survey. The performance of tasks by personnel is generally compared to a prescribed method documented in the SOPs and is assessed using inspections, surveillance, or audits. Initial verification audits and surveillances are designed to ensure that data collection activities are performed in accordance with established plans and procedures and should be conducted at the beginning of field activities. Conducting verification activities at the beginning of the survey process gives project management and personnel the opportunity to correct any data collection deficiencies before the completeness of the survey process is impacted. As specified in the QAPP, inspections, surveillances, and audits are necessary to ensure adherence to established SOPs and plans and that laboratory and field instruments are producing reliable results that meet the DQOs and MQOs. Self-assessments and independent assessments may be planned, scheduled, or performed as part of the survey. Self-assessment also means that personnel doing work should document deficiencies or problems that they encounter and report them to their supervisors or management.

The performance of equipment (such as radiation detectors) or measurement systems (such as instruments and human operators) can be monitored using control charts. Control charts are used to record the results of quantitative QC checks, such as background and daily calibration or performance checks. Control charts document instrument and measurement system performance on a regular basis and identify conditions requiring corrective actions in real time. Control charts are especially useful for surveys that extend over a significant period (e.g., weeks instead of days) and for equipment that is owned by a company and used frequently to collect survey data. Surveys that are accomplished in 1 or 2 days and use rented instruments may not benefit significantly from the preparation and use of control charts. SOPs usually document the use of control charts.

A technical review is an independent assessment that provides an in-depth analysis and evaluation of documents, activities, material, data, or items that require technical verification to ensure that established requirements are satisfied. A technical review typically requires a significant effort in time and resources and may not be necessary for all surveys. A complex survey using a combination of scanning, direct measurements, and sampling for multiple survey units is likely to benefit from a detailed technical review more than a simple survey design that calls for relatively few measurements using one or two measurement techniques for a single survey unit.

Performance evaluation of field survey instruments and laboratory sample measurement systems can include check sources to test their performance. As stated above, establishing control charts to check standard results on long-term projects is useful in evaluating field survey and laboratory sample measurements over time and looking for possible bias or precision trends that can be used in the data verification and validation process. Use of check source standards for short-term projects is beneficial in verifying performance. Performance evaluation samples sent to laboratories should be of a matrix that is similar to the actual sampling media and should contain radionuclides of similar concentrations to the anticipated residual radioactive material at the site.

D.4.2 Data Validation and Usability

Data validation activities confirm the extent to which the results of data collection activities support the objectives of the survey, as documented in the QAPP, or support a determination that these objectives should be modified. Data usability is the process of determining whether

the quality of the data produced meets the intended use of the data. Data verification compares the collected data with the prescribed activities documented in SOPs, and data validation compares the collected data to DQOs documented in the QAPP. Corrective actions can improve data quality, reduce uncertainty, and eliminate the need to qualify or reject future data.

Data validation is often defined by six data descriptors:

(1) reports to the decision-maker (**Section D.4.2.1**)
(2) documentation (**Section D.4.2.2**)
(3) data sources (**Section D.4.2.3**)
(4) measurement method uncertainty and detection capability (**Section D.4.2.4**)
(5) data review (**Section D.4.2.5**)
(6) DQIs (**Section D.4.2.6**)

The decision-maker or reviewer examines the data, documentation, and reports for each of the six data descriptors to determine whether performance is within the limits specified in the DQOs developed during survey planning. The data validation process should be conducted according to procedures documented in the QAPP.

Collected data should meet performance objectives for each data descriptor. If they do not, deviations should be noted, and any necessary corrective action should be performed to improve data usability when performance fails to meet objectives.

D.4.2.1 Reports to the Decision-Maker

Data and documentation supplied to the decision-maker should be evaluated for completeness and appropriateness and to determine whether any changes were made to the survey plan during the work. The survey plan discusses the surveying, sampling, and analytical design and implementation of the specifications of the QAPP and DQOs. The decision-maker should receive all data as collected plus preliminary and final data reports. The final decision on qualifying or rejecting data will be made during the validation assessment of environmental data. All data, including qualified or rejected data, should be documented and recorded, even if the data are not included in the final report.

Preliminary analytical data reports allow the decision-maker to begin the assessment process as soon as the surveying effort has begun. These initial reports have three functions:

(1) For scoping or characterization survey data, they allow the decision-maker to begin to characterize the site based on actual data. Radionuclides of interest will be identified and the variability in concentration can be estimated.

(2) They allow potential measurement problems to be identified, and the need for corrective action can be assessed.

(3) Schedules are more likely to be met if the planning of subsequent survey activities can begin before the final data reports are produced.

Table D-3 provides information on the six data descriptors.

Table D-3 Suggested Content or Consideration, Impact if Not Met, and Corrective Actions for Data Descriptors

Data Descriptor	Suggested Content or Consideration	Impact if Not Met	Corrective Actions
Reports to the Decision-Maker	• Site description • Survey design with measurement locations • Measurement method uncertainties and detection capabilities • Background radiation data • Results on a per-measurement basis with their associated uncertainties, qualified for analytical limitations • Field conditions for media and environment • Preliminary reports • Meteorological data, if indicated by DQOs • Field reports	• Unable to perform a quantitative RSSI	• Request missing information. • Perform qualitative or semi-quantitative site investigation.
Documentation	• Chain-of-custody records • SOPs • Field and analytical records • Measurement results related to geographic location	• Unable to identify appropriate concentration for survey unit measurements • Unable to have adequate assurance of measurement results	• Request that locations be identified. • Resurvey or resample. • Correct deficiencies.
Data Sources	• Historical data used meets DQOs	• Potential for Type I and Type II decision errors • Lower confidence of data quality	• Resurvey, resample, or reanalyze for unsuitable or questionable measurements.
Measurement Method Uncertainty and Detection Capability	• Routine methods used to quantify radionuclides of potential concern	• Potential for Type I and Type II decision errors	• Resurvey, resample, or reanalyze. • Document statements of limitation.

Data Descriptor	Suggested Content or Consideration	Impact if Not Met	Corrective Actions
Data Review	• Defined level of data review for all data	• Potential for Type I and Type II decision errors • Increased uncertainty due to analytical process, calculation errors, or transcription errors	• Perform data review.
DQIs	• Surveying and sampling variability identified for each radionuclide • QC measurements to identify and quantify precision and accuracy • Surveying, sampling, and analytical precision and accuracy quantified	• Unable to quantify levels for uncertainty • Potential for Type I and Type II decision errors	• Resurvey or resample. • Perform qualitative site investigation. • Document discussion of potential limitations.

D.4.2.2 Documentation

Field and laboratory documentation are used to perform data validation and to assess data usability. The types of field documentation assessed include field operation records and data handling records. The information contained in these records documents overall field operations and generally consists of the following:

- *Sample tracking records:* Sample tracking records (e.g., chain-of-custody records) document the progression of samples as they travel from the original sampling location to the laboratory and, finally, to disposal (**Section 7.8**).

- *QC measurement records:* QC measurement records document the performance of QC measurements in the field. These records should include traceability documentation for calibration and standards that can be used to provide a reproducible reference point to which all similar measurements can be correlated. QC measurement records should contain information on the frequency, conditions, level of standards, and instrument calibration history.

- *Personnel files:* Personnel files record the names and training certificates of the staff collecting the data.

- *General field procedures:* General field procedures (e.g., SOPs) record the procedures used in the field to collect data and outline potential areas of difficulty in performing measurements.

- *Deficiency and problem identification reports:* These reports document problems and deficiencies encountered, as well as suggestions for process improvement.

- *Corrective action reports:* Corrective action reports show what methods were used when general field practices or other standard procedures were violated and include the methods used to resolve noncompliance.

The types of laboratory documentation assessed in the validation process should include all the areas specified in Chapter 8 of MARLAP.

Data handling records document protocols used in data reduction, verification, and validation. Data reduction addresses data transformation operations, such as converting raw data into reportable quantities and units, using significant figures, and calculating measurement uncertainties. The records document procedures for handling data corrections.

D.4.2.3 Data Sources

Data source assessment involves the evaluation and use of historical analytical data. Historical analytical data should be evaluated according to DQIs and not the source of the data (e.g., analytical protocols may have changed significantly over time). DQIs are qualitative and quantitative descriptors used in interpreting the degree of acceptability or utility of data. Historical data sources, discussed in **Section 3.4.1,** are addressed during the HSA.

D.4.2.4 Measurement Method Uncertainty and Detection Capability

The selection of appropriate measurement methods based on detection capability and method uncertainty is important to survey planning. The detection capability of the method directly affects the usability of the data, because results near the lower detection limit have a greater possibility of false negatives and false positives. When the measurement method uncertainty becomes large compared to the variability in the radionuclide concentration, it becomes more difficult to demonstrate compliance using the guidance provided in MARSSIM.

The decision-maker compares detection capabilities (i.e., MDCs) with radionuclide-specific results to determine their effectiveness in relation to the DCGL. Assessment of preliminary data reports provides an opportunity to review the detection capabilities early and resolve any detection problems.

If the radionuclide result is below the MDC, the investigator should report the actual result of the analysis and should not report data as “less than the detection limit.” Even negative results and results with large uncertainties can be used in the statistical tests described in **Chapter 8.** Results reported as “<MDC” cannot be fully used and, for example, complicate even such simple analyses as calculating an average. When the MDC reported for a radionuclide is near the DCGL, the confidence in both identification and quantification may be low. Therefore, MARSSIM recommends that the MDC should be less than 50 percent of the DCGL. Information concerning nondetects or detections at or near MDCs should be qualified according to the degree of acceptable uncertainty.

The uncertainty of a measurement expressed as combined standard uncertainty is the square root of the sum of the squares of all the uncertainty components associated with the measurement method (see **Equation 6-23,** generally known as the error [uncertainty] propagation formula). The counting uncertainty is essentially a function of the square root of the number of net counts captured by instrumentation either as gross counts or for the number of counts on an isotope-specific basis (NRC 2004). Therefore, when choosing a measurement instrument for a particular isotope, the frequency of disintegrations for a given type of radioactivity (i.e., alpha versus gamma) for each radioactive isotope of interest should be

considered. Uncertainty factors associated with the measurement system for scanning and direct measurements can include variability in the distance between the detector surface and the sampling media, variability in the speed at which a detector passes over a survey point (or the amount of time the detector is held over the sampling point for direct measurements), the extent to which interference from other radioactive sources is minimized, and the extent to which human performance factors create variability in the measurement system. Uncertainty factors associated with sampling include variability in the sample collection methods and variability in the distribution of residual radioactive material in the sampling media. Laboratory uncertainty factors are discussed in Chapter 19 of MARLAP and can include variability in sample preparation, the sample geometry, and the inherent background in the laboratory.

D.4.2.5 Data Review

Data review begins with an assessment of the quality of analytical results and is performed by a professional with knowledge of the analytical procedures. Only data that are reviewed according to a specified level or plan should be used in the quantitative site investigation. Any analytical errors or limitations in the data that are identified by the review should be noted. An explanation of data qualifiers should be included with the review report.

All data should receive some level of review. Data that have not been reviewed should be identified, because the lack of review increases the uncertainty in the data. Unreviewed data may lead to Type I and Type II decision errors and may also contain transcription and calculation errors. Data may be used in the preliminary assessment before review but should be reviewed at a predetermined level before use in the final survey report.

Depending on the survey objectives, the level and depth of the data review vary. The level and depth of the data review may be determined during the planning process. The data review should include an examination of laboratory and method performance for the measurements and radionuclides involved. This examination includes the following:

- evaluation of data completeness
- verification of instrument calibration
- measurement of precision using duplicates, replicates, or split samples
- measurement of bias using reference materials or spikes
- examination of blanks for contamination
- assessment of adherence to method specifications and QC limits
- evaluation of method performance in the sample matrix
- applicability and validation of analytical procedures for site-specific measurements
- assessment of external QC measurement results and QA assessments

The results of this evaluation may indicate the need for a different level or depth of data review. Specific data review procedures are dependent on the survey objectives and should be documented in the QAPP.

Qualified data are any data that have been modified or adjusted as part of statistical or mathematical evaluation, data validation, or data verification operations. Data may be qualified or rejected as a result of data validation or data verification activities. Data qualifier codes or flags are often used to identify data that have been qualified. The QAPP and survey documentation should fully explain any scheme used. The following are examples of data

qualifier codes or flags derived from national qualifiers assigned to results under the Superfund Contract Laboratory Program (CLP)[6]:

U The associated value reported is a normal, not detected (less than critical value) result or less than the MDC. The sample was analyzed for the radionuclide of interest, but the radionuclide concentration was below the MDC. MARSSIM recommends reporting the actual result of the analysis, so this qualifier would inform the reader that the result reported is also below the MDC.

J The associated value reported is a modified, adjusted, or estimated quantity. This qualifier might be used to identify results based on surrogate measurements (see **Section 4.5.3**) or gross activity measurements (e.g., gross alpha, gross beta). The implication of this qualifier is that the estimate may be inaccurate or imprecise, which might mean the result is inappropriate for statistical evaluation. Surrogate measurements that are accurate or precise may or may not be associated with this qualifier. It is recommended that the potential uncertainties associated with surrogate or gross measurements be quantified and included with the results.

R The associated value reported is unusable. The result is rejected due to serious analytical deficiencies or QC results. These data would be rejected because they do not meet the DQOs of the survey.

D.4.2.6 Data Quality Indicators

The assessment DQIs presented in this section are important for determining data usability. The principal DQIs are precision (indicating random measurement error), bias (representing systematic measurement error), representativeness and detection capability, completeness, and comparability. Accuracy (indicating total measurement error) is the consideration of bias and precision together to determine how close given results are to the true concentration of residual radioactive material at a given location (EPA 2006c). Other DQIs affecting the RSSI process include the selection and classification of survey units, Type I and Type II decision error rates, the variability in the radionuclide concentration measured within the survey unit, and the LBGR or DL.

The major activity in determining the usability of data based on survey activities is assessing the effectiveness of measurements. Scanning and direct measurements taken during survey activities and samples collected for analysis should meet site-specific objectives based on scoping and planning decisions.

Determining the usability of analytical results begins with the review of QC measurements and qualifiers to assess the measurement result and the performance of the analytical method. If an error in the data is discovered, it is more important to evaluate the effect of the error on the data than to determine the source of the error. For some criteria, the documentation is reviewed as a whole. For other criteria, data are reviewed at the measurement level.

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[6] More information on the CLP National Functional Guidelines for Data Review is available at https://www.epa.gov/clp/superfund-clp-national-functional-guidelines-data-review.

Factors affecting the accuracy of identification and the precision and bias of quantification of individual radionuclides—such as calibration, MDCs, and recoveries—should be examined radionuclide by radionuclide. **Table D-4** summarizes the QC measurements and the data use implications.

Table D-4 Use of Quality Control Data

Quality Control Criteria	Effect on Identification When Criteria Are Not Met	Quantitative Bias Direction	Use
Spikes (Higher-Than-Expected Result)	Potential exists for incorrectly deciding a survey unit does not meet the release criteria.	High	Use data as upper limit.
Spikes (Lower-Than-Expected Result)	Potential exists for incorrectly deciding a survey unit does meet the release criteria.[a]	Low	Use data as lower limit.
Replicates (Inconsistent)	No effect exists, unless analyte is found in one duplicate but not the other.	High or Low[b]	Use data as estimate, but it may have poor precision.
Blanks (Contaminated)	Potential exists for incorrectly deciding a survey unit does not meet the release criteria.	High	Check for gross contamination or instrument malfunction.
Calibration (Bias)	Potential exists for decision errors.	High or Low[b]	Use data as estimate unless the problem is extreme.

[a] Only likely if recovery is near zero.
[b] Effect on bias determined by examination of data for each radionuclide.

D.4.2.6.1 Precision

Precision is a measure of agreement among replicate measurements of the same property under prescribed similar conditions. Precision is an indicator of the amount of random error in a measurement; when the precision is high, the random uncertainty is low. This agreement is calculated as either the range, variance, percent difference, or standard deviation. It may also be expressed as a percentage of the mean of the measurements, such as relative range (for duplicates) or coefficient of variation.

For scanning and direct measurements, precision may be specified for a single person performing the measurement or as a comparison between people performing the same measurement. For laboratory analyses, precision may be specified as either intra-laboratory (within a laboratory) or inter-laboratory (between laboratories). Precision estimates based on a single surveyor or laboratory represent the agreement expected when the same person or laboratory uses the same method to perform multiple measurements of the same location. Precision estimates based on two or more surveyors or laboratories refer to the agreement expected when different people or laboratories perform the same measurement using the same method.

The two basic activities performed in the assessment of precision are estimating the radionuclide concentration variability from the measurement locations and estimating the measurement uncertainty attributable to the data collection process. The level for each of these performance measures should be specified during development of DQOs. If the statistical

performance objectives are not met, additional measurements should be taken or one (or more) of the performance parameters changed.

Precision and random measurement uncertainty are Type A uncertainties under International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) Guide 98, "Guide to the Expression of Uncertainty in Measurement," originally published in 1993 (ISO/IEC 1993), that can be estimated using the results of replicate measurements, as discussed in **Chapter 6** for field measurements and **Chapter 7** for laboratory measurements. When collocated measurements are performed (in the field or in the laboratory), an estimate of total precision is obtained. When collocated samples are not available for laboratory analysis, a sample subdivided in the field and preserved separately can be used to assess the variability of sample handling, preservation, and storage, along with the variability in the analytical process, but variability in sample acquisition is not included. When only variability in the analytical process is desired, a sample can be subdivided in the laboratory before analysis.

Summary statistics, such as sample mean and sample variance, can assess the precision of a measurement system or component thereof for a project. These statistics may be used to estimate precision at discrete concentration levels or average estimated precision over applicable concentration ranges, or they may provide the basis for a continual assessment of precision for future measurements. Section 18.4.2 of MARLAP provides an equation for calculating the relative difference for radiochemistry duplicate analyses that accounts for the measurement uncertainties of the sample results. Additional methods for calculating and reporting precision are provided in EPA QA/G-8, "Guidance on Environmental Data Verification and Data Validation," issued November 2002 (EPA 2002b).

Table D-5 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for precision.

Table D-5 Minimum Considerations for Precision, Impact if Not Met, and Corrective Actions

Minimum Considerations for Precision	Impact When Minimum Considerations Are Not Met	Corrective Actions
• Confidence limit as specified in DQOs • Power as specified in DQOs • Minimum relative differences specified in the survey design and modified after analysis of background measurements if necessary • One set of field duplicates or more as specified in the survey design • Analytical duplicates and splits as specified in the survey design • Measurement method uncertainty specified	• Errors in decisions to act or not to act based on analytical data • Unacceptable level of uncertainty • Increased variability of quantitative results	For surveying and sampling— • Review field measurement protocols to ensure comparability of measurement techniques. • Add survey or sample locations based on information from available data that are known to be representative. • Adjust performance objectives. For analysis— • Analyze new duplicate samples. • Review laboratory protocols to ensure comparability. • Use precision measurements to determine confidence limits for the effects on the data. • Use the maximum measurement results to set an upper bound on the uncertainty if there is too much variability in the analyses.

D.4.2.6.2 Bias

Bias is the systematic or persistent distortion of a measurement process that causes errors in one direction. Bias is an indicator of the amount of systematic error in a measurement; when bias is high, then the systematic error is high. Bias assessments for radioanalytical measurements should be made using personnel, equipment, and spiking materials or reference materials as independent as possible from those used in the calibration of the measurement system. When possible, bias assessments of the measurement system should be based on certified reference materials rather than matrix spikes or water spikes. Matrix and water spikes are useful in evaluating the overall bias in the sampling and analytical processes, because the effect of the matrix and the chemical composition of the residual radioactive material is incorporated into the assessment. While matrix spikes include matrix effects, the addition of a small amount of liquid spike does not always reflect the chemical composition of the residual radioactive material in the sample matrix. Water spikes do not account for either matrix effects or the chemical composition of the residual radioactive material. When spikes are used to assess bias, a documented spiking protocol and consistency in following that protocol are important to obtaining meaningful data quality estimates.

Activity levels for bias assessment measurements should cover the range of expected radionuclide concentrations, although the minimum activity in the spike or reference material is usually at least five times the MDC. For many FSSs, the expected radionuclide concentration is zero or background, so the highest activity will be associated with the bias assessment measurements. The minimum and maximum concentrations allowable in bias assessment

samples should be agreed on during survey planning activities to prevent accidental contamination of the environment or of an environmental-level radioanalytical laboratory.

For scanning and direct measurements, a limited number of options are available for performing bias assessment measurements. Perhaps the best estimate of bias for scanning and direct measurements is obtained by collecting samples from locations where scans or direct measurements were performed, analyzing the samples in a laboratory, and comparing the results. Problems associated with this method include the time required to obtain the results and the difficulty in obtaining samples that are representative of the field measurement to provide comparable results. A simple method of demonstrating that analytical bias is not a significant problem for scanning or direct measurements is to use the instrument performance checks to demonstrate the lack of analytical bias. A control chart can be used to determine the variability of a specific instrument and track the instrument performance throughout the course of the survey. Field background measurements can also be plotted on a control chart to estimate bias caused by contamination of the instrument. In some circumstances, samples are collected and used to establish a correlation between survey measurements and laboratory measurements, with the correlation being used to adjust survey measurements to account for potential field measurement system bias.

Several types of bias assessment samples are available for laboratory analyses, as discussed in **Chapter 7.** Field blanks can be evaluated to estimate the potential bias caused by contamination from sample collection, preparation, shipping, and storage, and ambient concentration in the overall sampling and analysis process.

Table D-6 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for bias.

Table D-6 Minimum Considerations for Bias, Impact if Not Met, and Corrective Actions

Minimum Considerations for Bias	Impact When Minimum Considerations Are Not Met	Corrective Actions
• Matrix spikes to assess bias of nondetects and positive sample results if specified in the survey design • Analytical spikes as specified in the survey design • Use of analytical methods (routine methods whenever possible) that specify expected or required recovery ranges using spikes or other QC measures • No radionuclides of potential concern detected in the blanks	• Potential for incorrectly deciding a survey unit meets the release criteria: If a spike recovery is low, it is probable that the method or analysis is biased low for that radionuclide and that the values of all related samples may underestimate the actual concentration. • Potential for incorrectly deciding a survey unit does not meet the release criteria: If spike recovery is high, interferences may be present, and it is probable that the method or analysis is biased high and that analytical results overestimate the true concentration of the spiked radionuclide. • Potential for incorrectly deciding a survey does not meet the release criteria: Contamination in field or laboratory blanks results in overestimating the true concentration of the nuclide.	• Consider resampling at affected locations. • If recoveries are extremely low or extremely high, the investigator should consult with a radiochemist or health physicist to identify a more appropriate method for reanalysis of the samples. • If blanks indicate the presence of residual radioactive material, evaluate the impact of blanks on sample results near the $DCGL_W$ and assess sources of potential contamination to prevent recurrence of conditions leading to contamination.

D.4.2.6.3 Accuracy

Accuracy is a measure of the closeness of an individual measurement or the average of a number of measurements to the true value (EPA 2006c). Accuracy includes a combination of random error (precision) and systematic error (bias) components that result from performing measurements. Accuracy is an indicator of the total error in the measurement. **Chapter 6** discusses systematic and random uncertainties (or errors) in more detail.

Accuracy is determined by analyzing a reference material of known radionuclide concentration or by reanalyzing material to which a known concentration of radionuclide has been added. To be accurate, data must be both precise and unbiased. To use an analogy, an archer is only accurate when his or her arrows land close together and, on average, at the spot where they are aimed—in other words, the arrows must all land near the bull's eye (**Figure D-7**).

Accuracy is usually expressed either as a percent recovery or as a percent bias. Determination of accuracy always includes the effects of variability (representing precision); therefore, accuracy can be defined as a combination of bias and precision. The combination is known

statistically as mean square error. Mean square error is the quantitative term for the overall quality of individual measurements or estimators.

Mean square error is the sum of the variance plus the square of the bias. (The bias is squared to eliminate concern over whether it is positive or negative.) Frequently, it is impossible to quantify all the components of the mean square error—especially the biases—but it is important to attempt to quantify the magnitude of such potential biases, often by comparison with auxiliary data.

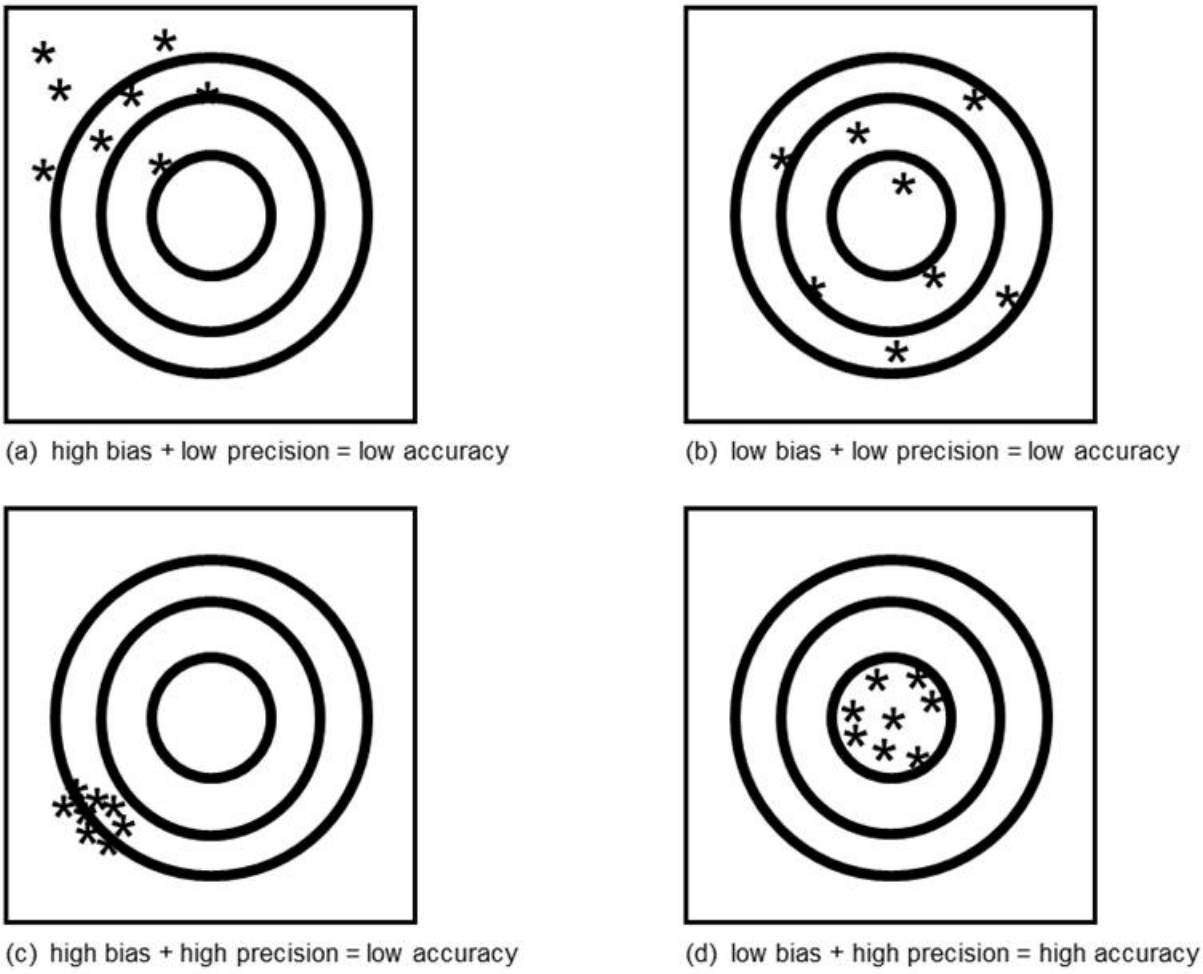


Figure D-7 Graphical Representation of Accuracy

D.4.2.6.4 Representativeness and Detection Capability

Representativeness is a measure of the degree to which a population of data represents a process condition or environmental condition. Representativeness is a qualitative term that should be evaluated to determine whether in situ and other measurements are made and physical samples collected in such a manner that the resulting data appropriately reflect the media and radionuclide measured or studied.

The representativeness of data is critical to assessments of data usability. The results of the environmental radiological survey will be biased to the degree that the data do not reflect the radionuclides and concentrations present at the site. Nonrepresentative radionuclide identification may result in false negatives. Nonrepresentative estimates of concentrations may be higher or lower than the true concentration. With few exceptions, nonrepresentative measurements are only resolved by additional measurements.

A significant component of representativeness is the detection capability of the survey measurements. Detection capability is the ability of the method or instrument to detect radionuclides at or below the level of interest. The MDC is the a priori activity concentration that a specific instrument and technique can be expected to detect 95 percent of the time. When stating the detection capability of an instrument, this value should be used. The MDC is the lower limit of detection, L_D, multiplied by an appropriate conversion factor to give units of activity. If the MDC is not sufficiently below the release criteria, then there will be a strong possibility that the detection capability is not representative of the measurement. MARSSIM recommends that the MDC should be less than 50 percent of the release criteria to ensure that the detection capability is sufficiently low.

Representativeness is primarily a planning concern. The solution to enhancing representativeness is in the design of the survey plan. Examples of representative issues that should be considered include the following:

- Decisions to use certain scanning or sampling/direct measurement must be made such that the measurement system detection capability is less than 50 percent of the release criteria.

- Decisions regarding where to collect measurements and the extent to which random measurement locations are selected will also impact the representativeness of the survey. Although judgmental measurements have valid uses in the survey process, sufficient random measurements must be collected to meet statistical considerations for the survey. Surveys that do not meet requirements for adequate numbers of random measurements may not be representative of the actual site.

- Decisions on how to collect measurements may also impact representativeness if the sample collection method is not amenable to the nature of deposition. For example, using swipe samples to measure fixed radiation would not be representative.

- Decisions as to what types of measurements or scan radiation to measure may impact representativeness if those radiations are not amenable for the radionuclides of interest.

The quality of analytical data also affects representativeness because data of low quality may be rejected for use, resulting in insufficient numbers of measurements. Alternatively, if the data associated with significant bias in one direction or another are estimates but are used to make release decisions, it is possible that an incorrect release decision may be made because of the bias. For example, if the data indicate that a survey unit is just below the established release criteria but the data are associated with significant low bias, it may be possible that the actual site conditions were actually above the release criteria and thus the data were not representative.

Table D-7 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for representativeness and detection capability.

Table D-7 Minimum Considerations for Representativeness and Detection Capability, Impact if Not Met, and Corrective Actions

Minimum Considerations for Representativeness and Detection Capability	Impact When Minimum Considerations Are Not Met	Corrective Actions
• Survey data are representative of the survey unit. • Sample preparation procedures are documented. Filtering, compositing, and sample preservation may affect representativeness. • Documented sample collection procedures are appropriate for the deposition at the site (fixed versus nonfixed). • Analytical data are documented as specified in the survey design. • MDCs are sufficiently below release criteria.	• Bias is high or low in estimating the extent and quantity of residual radioactive material. • Potential exists for incorrectly deciding a survey unit does meet the release criteria. • Inaccurate identification or estimate of the concentration of a radionuclide is possible. • Remaining data may no longer sufficiently represent the site if a large portion of the data is rejected or if all data from measurements at a specific location are rejected. • Data may not have sufficient detection capability to assess concentrations.	• Perform additional surveying or sampling. • Examine the effects of sample preparation procedures. • Reanalyze samples, or resurvey or resample the affected site areas. • If the resurveying, resampling, or reanalysis cannot be performed, document in the site environmental radiological survey report what areas of the site are not represented due to poor quality of analytical data. • Resurvey or resample using instrumentation and measurement systems of sufficient detection capability.

D.4.2.6.5 Comparability

Comparability is the qualitative term that expresses the confidence that two datasets can contribute to a common analysis and interpolation. Comparability should be carefully evaluated to establish whether two datasets can be considered equivalent for the measurement of a specific variable or groups of variables.

Comparability is not compromised if the survey design is unbiased and the survey design, survey measurement systems, sampling methods, and analytical methods are not changed over time. Comparability of survey measurement systems is dependent on ensuring that survey and direct measurement activities are performed according to established procedures and that survey variables, such as height from surface to detector, scanning speed, and direct measurement time, are consistent with specified project DQOs and MQOs. Comparability is a very important qualitative data indicator for analytical assessment and is a critical parameter when considering the combination of datasets from different analyses for the same radionuclides. The assessment of DQIs determines whether reported analytical results are equivalent to data obtained from similar analyses. Only comparable datasets can be readily combined.

The use of routine analytical methods (as defined in **Section 7.7**) simplifies the determination of analytical comparability, because all laboratories use the same standardized procedures and reporting parameters. In other cases, the decision-maker may have to consult with a health

physicist or radiochemist to evaluate whether different methods are sufficiently comparable to combine datasets.

A number of qualities can make two datasets comparable. The presence of each of the following items enhances the comparability of datasets (EPA 2006c):

- Two datasets should contain the same set of variables of interest.
- The units in which these variables were measured should be convertible to a common metric.
- Similar analytic and QA procedures should be used to collect data for both datasets.
- The time of measurements of certain characteristics (variables) should be similar for both datasets.
- Measuring devices used for both datasets should have similar detection capabilities.
- Rules for excluding certain types of observations from both samples should be similar.
- Samples within datasets should be selected in a similar manner.
- The sampling frames from which the samples were selected should be similar.
- The number of observations in both datasets should be of the same order of magnitude.

These characteristics vary in importance depending on the final use of the data. The closer two datasets are regarding these characteristics, the more appropriate it will be to compare them. Large differences between characteristics may be of only minor importance, depending on the decision that is to be made from the data.

Table D-8 presents the minimum considerations, impacts if they are not met, and corrective actions for comparability.

Table D-8 Minimum Considerations for Comparability, Impact if Not Met, and Corrective Actions

Minimum Considerations for Comparability	Impact When Minimum Considerations Are Not Met	Corrective Actions
• Either the unbiased survey design is chosen or the reasons for selecting another survey design are documented. • The analytical methods used should have common analytical parameters. • The same units of measure are used in reporting. • Detection limits are similar. • Sample preparation techniques are equivalent. • Analytical equipment has similar efficiencies, or the efficiencies are factored into the results.	• Nonadditivity of survey results • Reduced confidence, power, and ability to detect differences, given the number of measurements available • Increased overall error	• For surveying and sampling— – Perform a statistical analysis of the effects of bias. • For analytical data— – Preferentially use those data that provide the most definitive identification and quantitation of the radionuclides of potential concern. For quantitation, examine the precision and accuracy data along with the reported detection limits. – Perform a reanalysis using comparable methods.

D.4.2.6.6 Completeness

Completeness is a measure of the amount of valid data obtained from the measurement system, expressed as a percentage of the number of valid measurements that should have been collected (i.e., measurements that were planned to be collected). Valid data are all data that were found to be usable through the data verification and validation process.

Completeness for measurements is calculated by **Equation D-2:**

$$\% \text{ Completeness} = \frac{(\text{Number of Valid Measurements}) \times 100}{\text{Total Number of Measurements Planned}} \qquad \textbf{Equation D-2}$$

Completeness is not intended to be a measure of representativeness; that is, it does not describe how closely the measured results reflect the actual concentration or distribution of the radionuclide in the media being measured. A project could produce 100 percent data completeness (i.e., all planned measurements were performed and found valid), but the results may not be representative of the actual radionuclide concentration.

Alternatively, there could be only 70 percent data completeness (30 percent lost or found invalid), but, due to the nature of the survey design, the results could still be representative of the target population and yield valid estimates. The degree to which lack of completeness affects the outcome of the survey is a function of many variables, ranging from deficiencies in the number of measurements to failure to analyze as many replicates as deemed necessary by

the QAPP, DQOs, and MQOs. The intensity of effect due to incompleteness of data is sometimes best expressed as a qualitative measure and not just as a quantitative percentage.

Completeness can affect the DQO and MQO parameters. Lack of completeness may require reconsideration of the limits for decision error rates because insufficient completeness will decrease the power of the statistical tests described in **Chapter 8.**

For most FSSs, the issue of completeness arises only when the survey unit demonstrates compliance with the release criteria and less than 100 percent of the measurements are determined to be acceptable. The question now becomes whether the number of measurements is sufficient to support the decision to release the survey unit. This question can be answered by constructing a power curve (**Appendix M**) and evaluating the results. An alternative method is to consider that the number of measurements estimated to demonstrate compliance in **Section 5.3** is increased by 20 percent to account for lost or rejected data and uncertainty in the calculation of the number of measurements. This means that a survey with 80 percent completeness may still have sufficient power to support a decision to release the survey unit. Failure to complete a random start systematic grid in Class 1 survey units will affect the probability that the grid will detect elevated areas.

Table D-9 presents the minimum considerations, impacts if the considerations are not met, and corrective actions for completeness.

Table D-9 Minimum Considerations for Completeness, Impact if Not Met, and Corrective Actions

Minimum Considerations for Completeness	Impact When Minimum Considerations Are Not Met	Corrective Actions
• Percentage of measurement completeness is determined during planning to meet specified performance measures.	• Higher potential for incorrectly deciding that a survey unit does not meet the release criteria • Reduction in power • Reduced site coverage due to reduction in the number of measurements; may affect the ability to establish release criteria in parts or all of a survey unit • Reduced ability to differentiate site levels from background • Increased number of measurements, decreasing the impact of a set number of unusable or missing data points • Increased number of measurements, generally decreasing the impact of incompleteness	• Perform resurveying, resampling, or reanalysis to fill data gaps. • Perform additional analysis of samples already in laboratory. • Determine whether the missing data are crucial to the survey.

D.4.2.7 Selection and Classification of Survey Units

The selection and classification of survey units is a qualitative measure of the assumptions used to develop the survey plan. The level of survey effort, measurement locations (i.e., random versus systematic and density of measurements), and the integrated survey design are based on the survey unit classification. The results of the survey should be reviewed to determine whether they support the classification used to plan the survey.

If a Class 3 survey unit is found to contain areas of residual radioactive material (even if the survey unit passes the statistical tests), the survey unit may be divided into several survey units with appropriate classifications and additional surveys planned as necessary for these new survey units.

Class 3 areas may only require additional randomly located measurements to provide sufficient power to release the new survey units. Class 2 and Class 1 areas will usually require a new survey design based on systematic measurement locations, and Class 1 areas may require remediation before a new FSS is performed.

If a survey unit is incorrectly identified as Class 2 but the FSS determines the survey unit to be Class 1 and remediation is not required, it may not be necessary to plan a new survey. The scan MDC should be compared to the $DCGL_{EMC}$ to determine whether the measurement spacing is adequate to meet the survey objectives. If the scan MDC is too high, a new scan survey using a more sensitive measurement technique may be available. Alternatively, a new survey may be planned using a new measurement spacing, or a stratified survey design may be implemented to use as much of the existing data as possible.

D.4.2.7.1 Decision Error Rates

The decision error rates developed during survey planning are related to completeness. A low level of completeness will affect the power of the statistical test. MARSSIM recommends that a retrospective power analysis at the $DCGL_W$ be completed as described in **Appendix M** and the expected decision error rates be compared to the actual decision error rates to determine whether the survey objectives have been accomplished.

D.4.2.7.2 Variability in Radionuclide Concentration

The variability in the radionuclide concentration (in both the survey unit and the reference area) is a key parameter in survey planning and is related to the precision of the measurements. Statistical simulations show that underestimating the value of σ (the standard deviation of the survey unit measurements) can greatly increase the probability that a survey unit will fail to demonstrate compliance with the release criteria.

If a survey unit fails to demonstrate compliance and the actual σ is greater than the σ used during survey planning, several options are available to the project manager. If the major component of variability is measurement uncertainty, a new survey can be designed using a measurement technique with lower measurement method uncertainty to reduce variability. If samples were collected as part of the survey design, it may only be necessary to reanalyze the samples using a method with lower measurement method uncertainty rather than collect additional samples. Alternatively, the number of measurements can be increased to reduce the variability.

If the variability is due to actual variations in the radionuclide concentration, there are still options available. If the variability is caused by different radionuclide distributions in different parts of the site (e.g., changing soil types influences contaminant concentrations), it may be appropriate to redefine the survey unit boundaries to provide a more homogeneous set of survey units.

D.4.2.7.3 Lower Bound of the Gray Region or Discrimination Limit

In Scenario A, the LBGR is used to calculate the relative shift, which, in turn, is used to estimate the number of measurements required to demonstrate compliance. The LBGR is typically chosen to represent a conservative (slightly higher) estimate of the residual radioactive material concentration remaining in the survey unit at the beginning of the FSS. If there is no information with which to estimate the residual radioactive material concentration remaining, the LBGR may be set initially to equal one-half of the $DCGL_W$. However, this is arbitrary as it does not make use of data from prior surveys to assess the quality of the remediation. Therefore, doing so should be considered only as a last resort. This becomes important because the Type II decision error rate is calculated at the LBGR. The width of the gray region (DCGL − LBGR = Δ) is a major factor in determining the number of samples to take in the survey unit.

In Scenario B, the gray region is defined as the interval between the AL and the DL. The DL is a concentration or level of radioactive material that can be reliably distinguished from the AL by performing measurements with the devices selected for the survey (i.e., direct measurements, scans, in situ measurements, samples and laboratory analyses). The DL defines the rigor of the survey and is determined through negotiations with the regulator.

In Scenario A, for survey units that pass the statistical tests, the value selected for the LBGR is generally not a concern. If the survey unit fails to demonstrate compliance, it may be caused by improper selection of the LBGR. Because the number of measurements estimated during survey planning is based on the relative shift (which includes both σ and the LBGR), MARSSIM recommends completion of a retrospective power analysis at the $DCGL_W$ as described in **Appendix M.** If the survey unit failed to demonstrate compliance because of a lack of statistical power, an adjustment of the LBGR may be necessary when planning subsequent surveys.

In Scenario B, the DL is a chosen value as part of the planning process and does not necessarily represent a physical characteristic of the survey unit. However, a retrospective power analysis at the DL should be completed to guard against insufficient power when the survey unit passes the statistical tests.

APPENDIX E
EFFECT OF PRECISION ON PLANNING AND PERFORMING SURVEYS

E.1 Introduction

This appendix includes three examples demonstrating the potential consequences of using methods with different levels of precision for planning and designing a final status survey (FSS) and for actually performing the FSS. **Example E-1** illustrates the use of precise measurement methods for planning and performing the FSS. The use of less precise measurement methods for both planning and performing the FSS is shown in **Example E-2. Example E-3** implements the use of a precise measurement method for planning and a less precise method for performing the FSS. It is important to note that greater uncertainty or variability that may result from either measurement uncertainty or an underestimation of true spatial variability must be accounted for during planning.

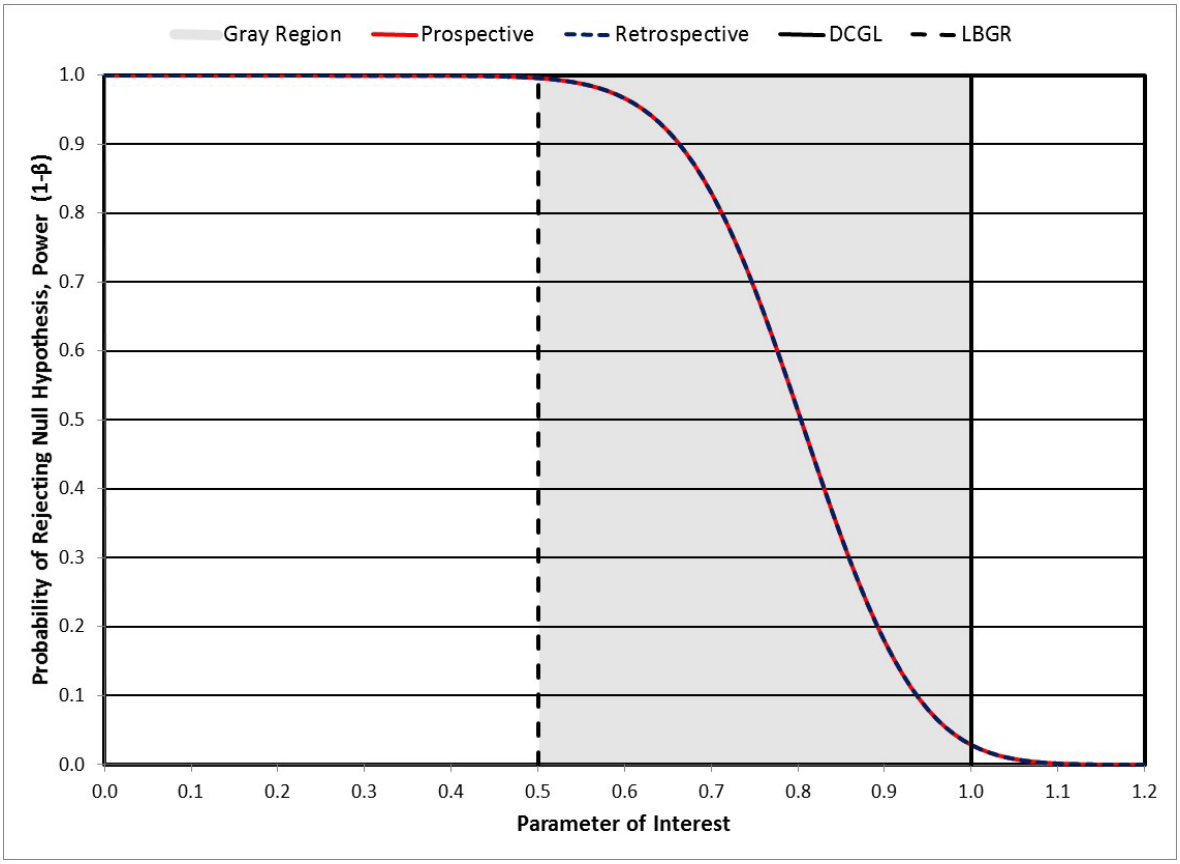
Example E-1: Precise Measurements Methods Used for Both Planning and Performing the FSS

Using a precise measurement method, the FSS planning sample size and a power curve (**Appendix M**) for the Sign test are generated by calculating an estimate of the mean,[1] used to establish the lower bound of the gray region (LBGR), and the standard deviation, σ, using the applicable scoping, characterization, or remedial action support data. The derived concentration guideline level (DCGL) is set to 1. The actual FSS mean—calculated by taking the average of the FSS sample analytical results—was higher than the planning mean (0.7 versus 0.5), as shown in the table below.

Measurement Method for Planning: Precise	Measurement Method for Assessment: Precise
Population Parameters for Planning:	Population Parameters for Assessment:
DCGL = 1	DCGL = 1
$\bar{x} \pm \sigma = 0.5 \pm 0.3$	$\bar{x} \pm \sigma = 0.7 \pm 0.3$

The prospective and retrospective power curves below are shown for the same precise measurement method (σ had been accurately estimated and did not change). The prospective power curve shows the planned power of at least 0.9 at the LBGR and the retrospective power achieved (~0.83) when the actual mean was 0.7 and the variability was adequately estimated with the same precise measurement method as was used to analyze the samples collected for planning. Overall, this shows a relatively minor loss of power at the actual, observed mean concentration.

[1] In the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), “average” and “mean” both refer to the arithmetic mean.



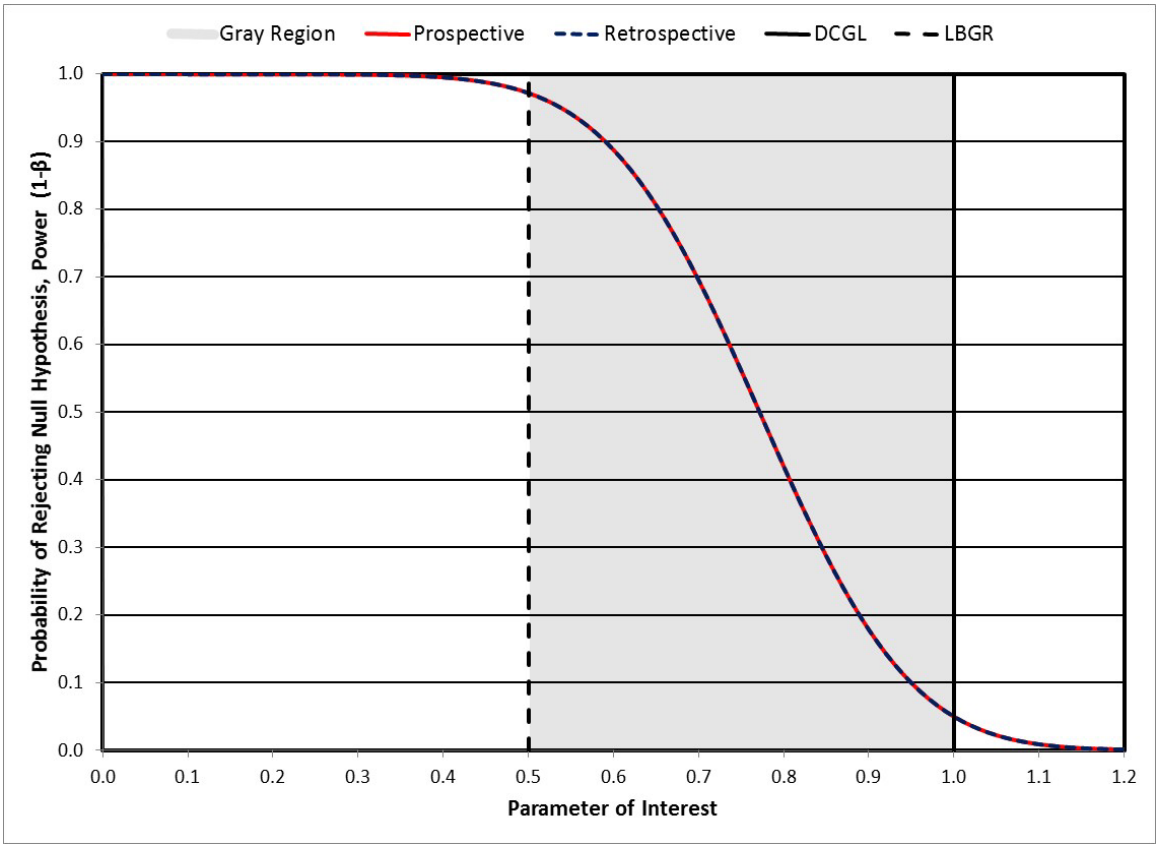
Prospective and Retrospective Power Curves for $N = 14$, $\alpha = 0.05$, and $\sigma = 0.3$

Example E-2: Less Precise Measurement Methods Used for Both Planning and Performing the FSS

Using a less precise measurement method, the FSS planning sample size and a prospective power curve for the Sign test are generated with the mean (LBGR) and σ. The planning and assessment means are the same as in **Example E-1,** but in this case, the σ increased compared to **Example E-1** due to the less precise measurements, as shown in the table.

Measurement Method for Planning: Less Precise	Measurement Method for Assessment: Less Precise
Population Parameters for Planning:	Population Parameters for Assessment:
DCGL = 1	DCGL = 1
$\bar{x} \pm \sigma = 0.5 \pm 0.6$	$\bar{x} \pm \sigma = 0.7 \pm 0.6$

The prospective and retrospective power curves are shown in the figure below using the same less precise measurement method (σ did not change from the planning to final stages). Although the sample population more than doubled compared to **Example E-1**, due to the higher σ associated with the less precise measurement technique, the retrospective power of 0.83 seen in **Example E-1** was not maintained at the actual FSS mean of 0.7. Rather, power reduced to ~0.70, as seen below. An even larger sample population would be required to maintain the same power at the observed mean provided in **Example E-1.**



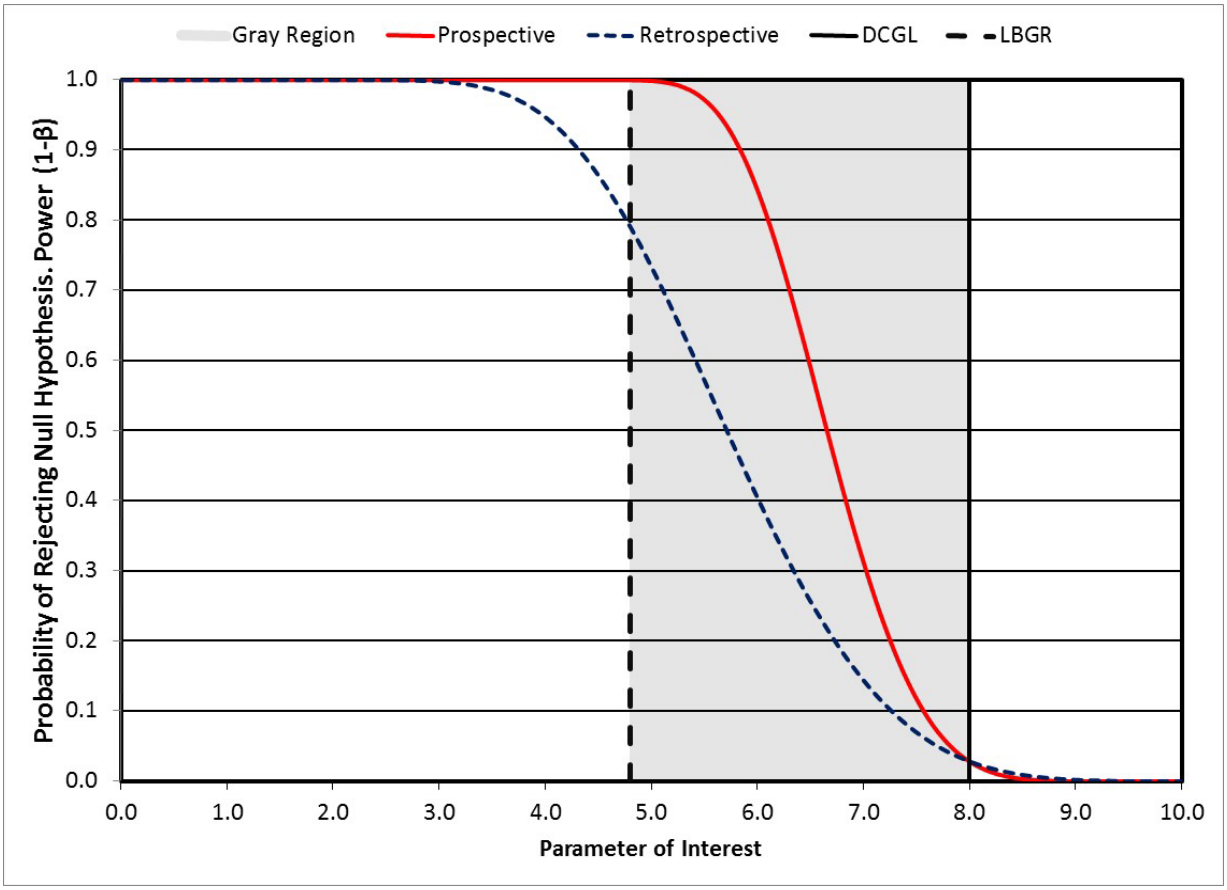
Prospective and Retrospective Power Curves for $N = 30$, $\alpha = 0.05$, and $\sigma = 0.6$

Example E-3: Precise Measurement Method Used for Planning and a Less Precise Method Used for Performing the FSS

For this example, the FSS planning sample size and a prospective power curve for the Wilcoxon Rank Sum test are generated using the mean (LBGR) and σ obtained from planning samples that had been analyzed by a precise measurement method. The inputs to the design are provided below. The FSS samples were analyzed by a less precise method. As seen in the assessment data below, the less precise method resulted in increased uncertainty of the mean. The uncertainty in the mean could have also been underestimated during the planning stage due to improper accounting of true spatial variability.

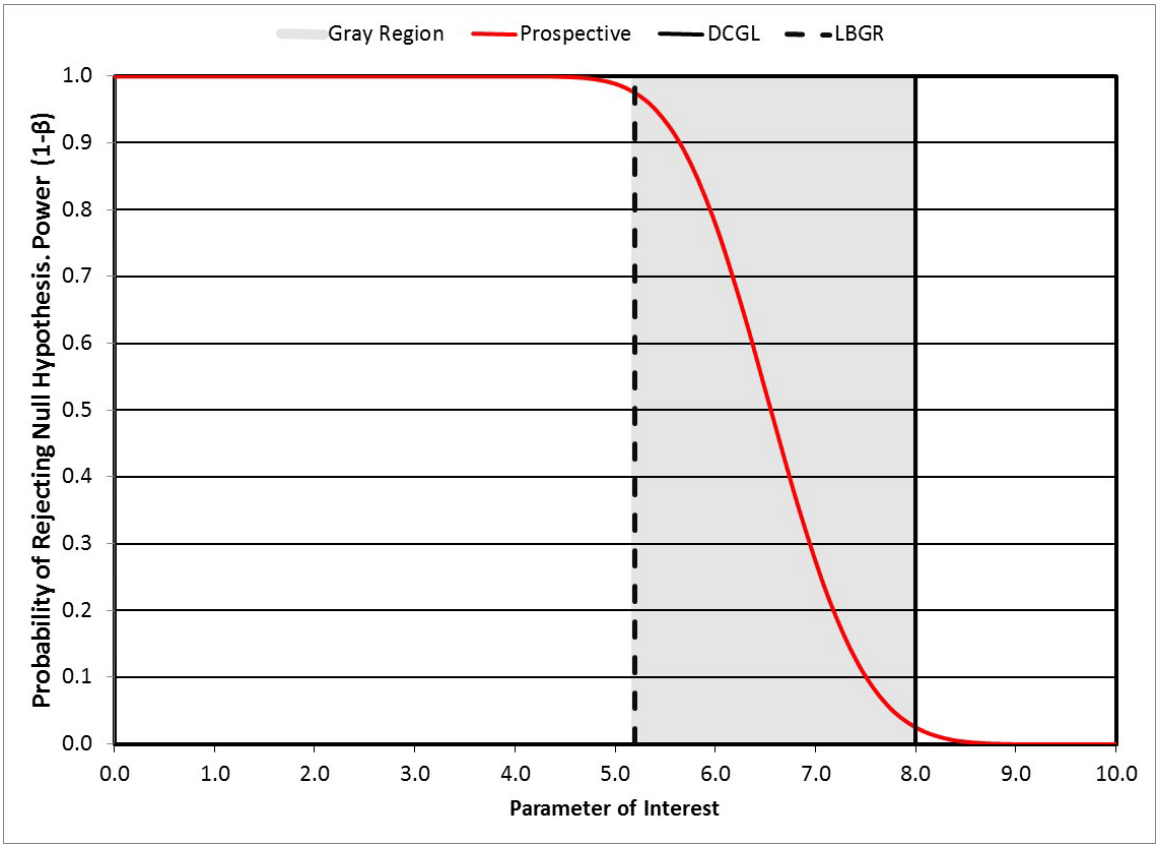
Measurement Method for Planning: Precise	Measurement Method for Assessment: Less Precise
Population Parameters for Planning:	Population Parameters for Assessment:
DCGL = 8	DCGL = 8
$\bar{x} \pm \sigma = 4.8 \pm 1.7$ $N / 2 = 14$	$\bar{x} \pm \sigma = 5.2 \pm 2.9$ $m = n = 14$

As seen in the figure below, the retrospective power at the actual mean has decreased to about 0.67, and additional samples would have been required to maintain the same power.



Prospective and Retrospective Power Curves for $m = n = 14$, $\alpha = 0.05$, and $\sigma = 1.7$ for the prospective power curve and $\sigma = 2.9$ for the retrospective power curve

The figure below illustrates a revised plan, which accounts for the additional uncertainty. The increased uncertainty of the mean that was obtained with the less precise method results in a much larger sample population of $N / 2 = 34$ to maintain the same power of 0.90 as originally planned.



Prospective Power Curve for $N / 2 = 34$, $\alpha = 0.05$, and $\sigma = 2.9$

E.2 Summary

In summary, greater uncertainty that may result from a less precise (higher uncertainty) measurement system (or true spatial variability) must be accounted for during planning; otherwise, sufficient samples may not be collected to maintain statistical power, and more survey units than expected may fail due to insufficient survey design for Scenario A, thereby requiring that survey units be resurveyed. For Scenario B, insufficient power could lead to a need for resurvey to ensure the survey unit was not released due to insufficient power. This will be particularly important if precise measurement data were used to establish the relative shift value and less precise data are generated during the FSS for the data assessment phase of the data life cycle. When using less precise methods, the planning team should[2] fully evaluate the impacts of prospective data planning and retrospective data assessment on decision-making. There will be a point at which the potential benefit of increased measurements from a less precise measurement technique will be offset by the impact of less precise measurements. Various scenario calculations may be required to predict at what point the increase in the sample population makes up for the greater uncertainty of the less precise measurements.

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[2] MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

APPENDIX F
THE RELATIONSHIP BETWEEN THE RADIATION SURVEY AND SITE INVESTIGATION PROCESS, THE CERCLA REMEDIAL OR REMOVAL PROCESS, AND THE RCRA CORRECTIVE ACTION PROCESS

This appendix discusses the relationship between the Radiation Survey and Site Investigation Process; the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Remedial or Removal Process; and the Resource Conservation and Recovery Act (RCRA) Corrective Action Process. Each of these processes has been designed to incorporate survey planning using the Data Quality Objectives process and data interpretation using Data Quality Assessment, employing a series of surveys to accomplish the project objectives. At this basic level, the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) is consistent with the other processes.

Figure F-1 compares the major steps in each of these processes. As shown in **Figure F-1,** the scope of MARSSIM (**Section 1.1**) results in steps in the CERCLA Remedial or Removal Process or the RCRA Corrective Action Process that are not directly addressed by MARSSIM (e.g., feasibility study [FS] or corrective measures study). MARSSIM's focus on the demonstration of compliance for sites with residual radioactive material using a final status survey (FSS) integrates with the remedial design/remedial action step of the CERCLA Remedial Process described in Title 40 of the *Code of Federal Regulations* (CFR) 300.435(b)(1). However, MARSSIM's focus is not directly addressed by the major steps of the CERCLA Removal Process and the RCRA Corrective Action Process.

Much of the information presented in MARSSIM for designing surveys and assessing the survey results is taken directly from the corresponding CERCLA or RCRA guidance. MARSSIM users familiar with the Superfund preliminary assessment guidance (EPA 1991a) will recognize the information provided on performing the Historical Site Assessment (**Chapter 3**) for identifying soil, water, or sediment potentially affected by residual radioactive material. In addition, MARSSIM provides information on identifying structures potentially affected by residual radioactive material that is not covered in the original CERCLA guidance. The survey designs and statistical tests for relatively uniform distributions of residual radioactive material discussed in MARSSIM also are discussed in CERCLA guidance (EPA 1989b, 1994b). However, MARSSIM includes scanning for radioactive material, which is not discussed in the more general CERCLA guidance that does not specifically address radionuclides. MARSSIM is not designed to replace or conflict with existing CERCLA or RCRA guidance; it is designed to provide supplemental information on specific applications of the CERCLA Remedial or Removal Process or the RCRA Corrective Action Process.

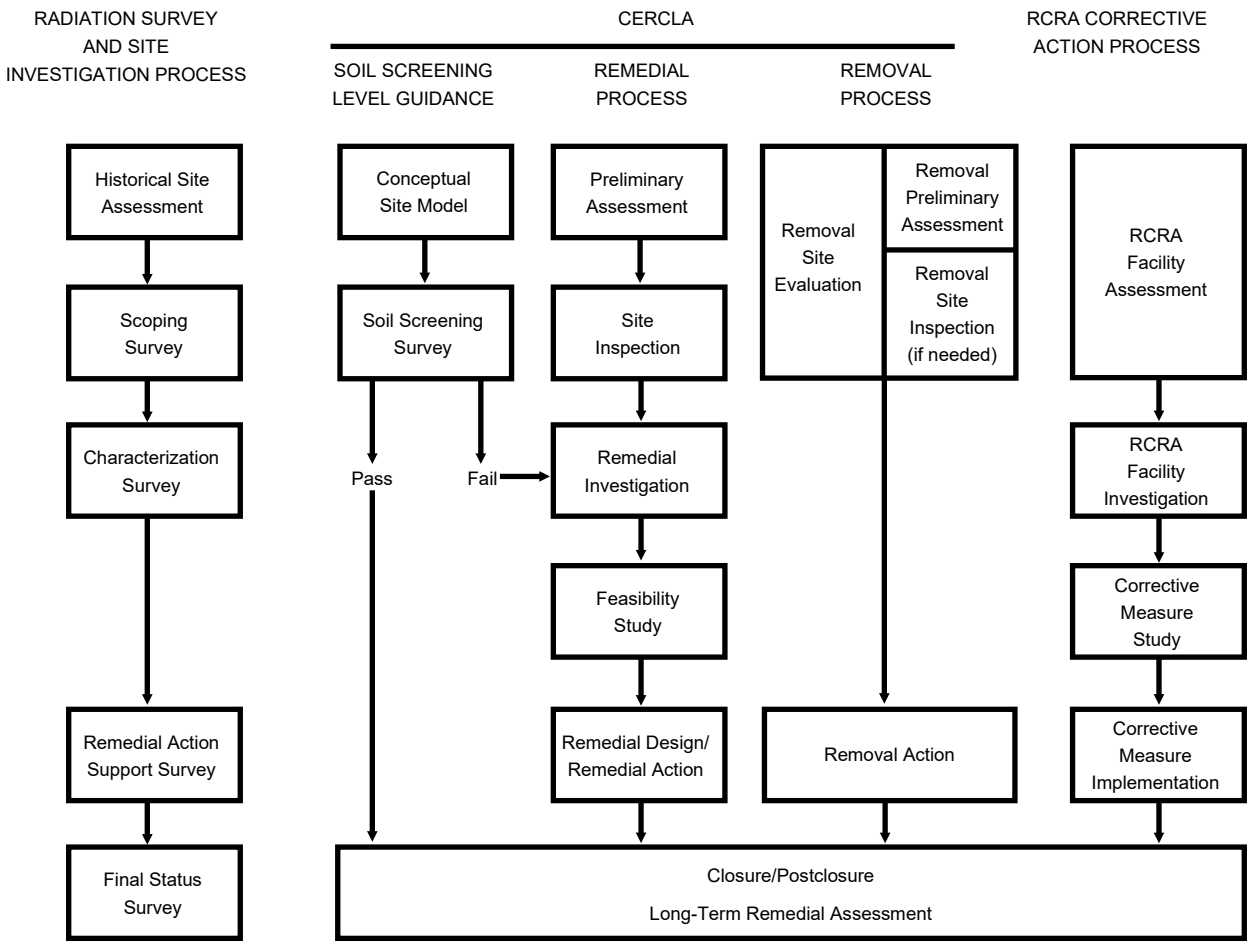

Figure F-1 Comparison of the Radiation Survey and Site Investigation Process with the CERCLA Superfund Process and the RCRA Corrective Action Process

Table F-1 lists the major steps in MARSSIM and other CERCLA and RCRA processes and describes the objectives of each step. This table provides a direct comparison of these processes, and it shows the correlation among the processes. This correlation is the result of carefully integrating CERCLA and RCRA guidance with guidance from other agencies participating in the development of MARSSIM to produce a multiagency consensus technical document.

The first step in the CERCLA Remedial Process is the preliminary assessment to obtain existing information about the site and determine whether there is a threat to human health and the environment. The next step is the site inspection, which includes risk prioritization using the Hazard Ranking System—sites with a score above a certain level are put on the National Priorities List (NPL). Following the remedial site assessment, the remedial investigation (RI) is performed to characterize the extent and type of release and to evaluate the risk to human health and the environment. A sampling and analysis plan is constructed as part of the RI, which consists of a Quality Assurance Project Plan (QAPP), a field sampling plan, a health and safety plan, and a community relations plan. The site FS, which involves an evaluation of alternative remedial actions, is the next step in the CERCLA Remedial Process (although the RI

and FS are intended to be done concurrently). For sites listed on the NPL, the next action would be to obtain a record of decision, which provides the remedy selected for the site. The remedial design/remedial action, which includes the development of the selected remedy and its implementation, follows preparation of the record of decision. After the remedial design/remedial action activities, there is a period of operation and maintenance when the site is given a long-term remedial assessment, followed by closure/postclosure of the site (or removal from the NPL). A removal action may occur at any stage of the CERCLA Remedial Process.

The CERCLA Removal Process is similar to the CERCLA Remedial Process for the first few steps. Subpart E, "Hazardous Substance Response," of 40 CFR Part 300, "National Oil and Hazardous Substances Pollution Contingency Plan," establishes methods and criteria for determining the extent of response when there is a release into the environment of a hazardous substance or any pollutant or contaminant that may present an imminent and substantial danger to the public health or welfare of the United States. The first step in the CERCLA Removal Process is a site evaluation, which includes a preliminary assessment and, if warranted, a site inspection. A removal preliminary assessment may be based on available information and should[1] include an evaluation of the factors necessary to determine whether a removal action is necessary. A removal site inspection is performed, if warranted, in a manner similar to that in the CERCLA Remedial Process. If environmental samples are to be collected, a sampling and analysis plan should be developed, which consists of a field sampling plan and a QAPP. Post-removal site controls are those activities necessary to sustain the effectiveness and integrity of the removal action. In the case of all CERCLA removal actions taken pursuant to 40 CFR 300.415, "Removal action," a designated spokesperson will inform the community of actions taken, respond to inquiries, and provide information concerning the release—this may include a formal community relations plan specifying the community relations activities expected during the removal response.

The CERCLA Remedial Process and the CERCLA Removal Process have been compared (EPA 1993a). **Table F-2** presents the data elements that are common to both programs and those that are generally part of one program and not the other. **Table F-3** shows the emphasis placed on sampling for remedial site assessment versus removal site assessment.

Additional guidance documents that can be compared to MARSSIM are the U.S. Environmental Protection Agency (EPA) Soil Screening Guidance (EPA 1996a, EPA 1996b), its supplement for Superfund sites (EPA 2002c), and the EPA Soil Screening Guidance for Radionuclides (EPA 2000a, EPA 2000b), which facilitate removing sites from consideration early in the CERCLA process. This early step is similar to the MARSSIM categorization process for determining whether a portion of a site is impacted or non-impacted. These combined soil screening guidance (SSG) documents lead the user from the initial site conceptualization and planning stages through data collection and evaluation to the final testing step. MARSSIM also leads the user through similar planning, evaluation, and testing stages, but MARSSIM focuses on the final compliance demonstration step.

The user's guides for the SSG documents provide details for implementing a simple methodology for calculating site-specific soil screening levels (SSLs). Technical background documents present generic SSLs and the technical foundation for the methodology for

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[1] MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

establishing SSLs. An electronic version of the risk assessment and groundwater leaching equations in the SSG for radionuclides is available for calculating site-specific SSLs and preliminary remediation goals (PRGs) that account for radioactive decay and ingrowth.

Both the SSG and MARSSIM provide examples of acceptable sampling and analysis plans for residual radioactive materials. The SSG-recommended default survey design for surface soils is very specific, and it describes in detail the recommendations for the sampling grid size, the number of soil samples collected from each subarea and composited, and data analysis and interpretation techniques. MARSSIM provides information that is consistent and compatible with the SSG with respect to the approaches, framework, tools, and overall objectives.

SSLs calculated using the CERCLA SSG also could be used for RCRA Corrective Action Process sites as action levels. The RCRA Corrective Action Program views action levels as generally fulfilling the same purpose as SSLs. **Table F-1** shows other similarities between the RCRA Corrective Action Process, CERCLA Remedial or Removal Process, and MARSSIM.

The similarities between the CERCLA Remedial Process and the CERCLA Removal Process have led to several streamlined approaches to expedite site cleanups by reducing the number of samples and minimizing duplication of effort. One example of these approaches is the Triad Method, which is a technically defensible methodology for managing decision uncertainty by leveraging innovative characterization tools and strategies. The Triad Method refers to three primary components: (1) systematic planning, (2) dynamic work strategies, and (3) real-time measurement systems (EPA 2005c, 2007, 2010). A memorandum from the EPA, U.S. Department of Energy (DOE), and U.S. Department of Defense (DoD) (DOE, EPA, DoD 1994) discusses guidance on accelerating and developing streamlined approaches for the cleanup of hazardous waste at Federal facility sites.

Table F-1 Program Comparison

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA CORRECTIVE ACTION PROCESS
Historical Site Assessment Performed to gather existing information about radiation sites. Designed to distinguish between sites that have no potential for residual radioactive material and those that require further investigation. Performed in three stages: 1. site identification 2. preliminary investigation 3. site reconnaissance	Preliminary Assessment Performed to gather existing information about the site and surrounding area. Emphasizes obtaining comprehensive information on people and resources that might be threatened by a release from the site. Designed to distinguish between sites that pose little or no threat to human health and the environment and sites that require further investigation.	Preliminary Assessment Performed in a similar manner as in the CERCLA Remedial Process. May be based on available information. May include identification of the source(s), nature and magnitude of the release, Agency for Toxic Substances and Disease Registry evaluation of the threat to public health, and factors to determine whether a removal action is necessary.	RCRA Facility Assessment Performed to identify and gather information at RCRA facilities, make preliminary determinations regarding releases of concern, and identify the need for further actions and interim measures at the facility. Performed in three stages: 1. preliminary review 2. visual site inspection 3. sampling visit (if necessary) The RCRA facility assessment accomplishes the same objectives as the CERCLA preliminary assessment and site inspection. The RCRA facility assessment often forms the basis for the first conceptual model of the site.

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA CORRECTIVE ACTION PROCESS
Scoping Survey Performed to provide a preliminary assessment of the radiological hazards of the site. Supports categorization and classification determinations of impacted and non-impacted areas of the site. Provides data to complete site prioritization using the Hazard Ranking System for CERCLA and RCRA sites.	Site Inspection Performed to identify substances present, determine whether hazardous substances are being released to the environment, and determine whether hazardous substances have impacted specific entities. Designed to gather information on identified sites in order to complete the Hazard Ranking System to determine whether a removal action or further investigation is necessary.	Site Inspection Performed in a manner similar to the CERCLA Remedial Process. May be performed as part of the removal site evaluation (40 CFR 300.410) if warranted. May include a perimeter or onsite inspection. If the removal site evaluation shows that a removal action is not required but that remedial action under 40 CFR 300.430 may be necessary, a remedial site evaluation pursuant to 40 CFR 300.420 would be initiated.	See above

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA CORRECTIVE ACTION PROCESS
Characterization Survey Performed to support planning for FSSs to demonstrate compliance with a dose- or risk-based regulation. Objectives include determining the nature and extent of residual radioactive material at the site, as well as meeting the requirements of the RI/FS and facility investigation/corrective measures study.	Remedial Investigation Performed to characterize the extent and type of release of contaminants. The RI is the mechanism for collecting data to characterize site conditions, determine the nature of the contaminant, assess risk to human health and the environment, and conduct treatability testing as necessary to evaluate the potential performance and cost of the treatment technologies being considered.	Removal Action Performed once the decision has been made to conduct a removal action at the site (under 40 CFR 300.415). Whenever a planning period of at least 6 months exists before onsite activities must be initiated, an engineering evaluation/cost analysis or its equivalent is conducted.	RCRA Facility Investigation (RFI) Defines the presence, magnitude, extent, direction, and rate of movement of any hazardous wastes and hazardous constituents within and beyond the facility boundary. The scope is to do the following: • Characterize the potential pathways of contaminant migration. • Characterize the source(s) of contamination. • Define the degree and extent of contamination. • Identify actual or potential receptors.

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA CORRECTIVE ACTION PROCESS
Characterization Survey (continued)	EPA guidance presents a combined RI/FS model statement of work. The RI is generally performed in seven tasks: 1. project planning (scoping): • summary of site location • history and nature of problem • history of regulatory and response actions • preliminary site boundary • development of site operations plans 2. field investigations 3. sample/analysis verification 4. data evaluation 5. assessment of risks 6. treatability study/pilot testing 7. RI reporting	If environmental samples are to be collected, a sampling and analysis plan is developed to provide a process for obtaining data of sufficient quality and quantity to satisfy data needs. The sampling and analysis plan consists of two parts: 1. the field sampling plan, which describes the number, type, and location of samples and the type of analysis to be performed on the collected samples 2. the QAPP, which describes the policy, organization, functional activities, measures, and Data Quality Objectives necessary to achieve adequate data for use in the removal action	• Support the development of alternatives from which the EPA will select a corrective measure. The RFI is performed in seven tasks: 1. description of current conditions 2. identification of preliminary remedial measures technologies 3. RFI work plan requirements • project management plan • data collection QAPP • data management plan • health and safety plan • community relations plan 4. facility investigation 5. investigation analysis 6. laboratory and bench-scale studies 7. reports

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA CORRECTIVE ACTION PROCESS
Derived Concentration Guideline Levels (DCGLs) Residual concentration levels of radioactive material that correspond to allowable radiation dose or risk standards that are calculated and provided to the user. The survey unit is then evaluated against this radionuclide-specific DCGL. The DCGLs in this manual are for residual radioactive material on structure surfaces and surface soils. MARSSIM does not provide equations or information on calculating DCGLs.	Preliminary Remediation Goals Developed early in the RI/FS process. PRGs then may be used as the basis for final cleanup levels based on the nine criteria in the National Contingency Plan. SSLs can be used as PRGs, provided that conditions at a specific site are similar to the default values used in calculating the SSLs. SSLs are derived with exposure assumptions for suburban residential land use only. SSLs are based on 10^{-6} risk for carcinogens and a hazard index quotient of 1 for noncarcinogens (using child ingestion assumptions); or maximum contaminant level goals, maximum contaminant levels, or health-based levels for contaminant migration into groundwater. The SSG user's guide (EPA 1996b) provides equations and guidance for calculating site-specific SSLs.	Removal Levels Established by identifying applicable or relevant and appropriate requirements, or by health assessments. Concern is for protection of human health and the environment from the immediate hazard of a release rather than a permanent remedy.	Action Levels At facilities that are subject to RCRA corrective action(s), contamination will be present at concentrations that may not justify further study or remediation. Action levels are health- or environmentally based concentrations derived using chemical-specific toxicity information and standardized exposure assumptions. The SSLs developed under CERCLA guidance can be used as action levels because the RCRA Corrective Action Program currently views them as serving the same purpose.

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA CORRECTIVE ACTION PROCESS
No Direct Correlation (MARSSIM characterization and remedial action support surveys may provide data for the FS or the corrective measures study.)	Feasibility Study Serves as the mechanism for the development, screening, and detailed evaluation of alternative remedial actions. As noted above, the RI and the FS are intended to be performed concurrently. Usually considered to be composed of four general tasks: 1. development and screening of remedial alternatives 2. detailed analysis of alternatives 3. community relations 4. FS reporting	No Direct Correlation	Corrective Measures Study Identify, develop, and evaluate potentially applicable corrective measures and recommend the corrective measures to be taken. Performed following an RFI and consists of four tasks: 1. identification and development of the corrective measures alternatives 2. evaluation of the corrective measures alternatives 3. justification and recommendations for the corrective measures alternatives 4. reports

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA CORRECTIVE ACTION PROCESS
Remedial Action Support Survey Performed to support remediation activities and determine when a site or survey unit is ready for the FSS. These surveys, not as thorough as the FSS, serve to determine the effectiveness of ongoing decontamination efforts to reduce residual radioactive material to acceptable levels. Excludes routine operational surveys that are conducted to support remedial activities.	Remedial Design/Remedial Action Includes the development of the selected remedy and implementation of the remedy through construction. A period of operation and maintenance may follow the remedial design/remedial action activities. Generally includes five elements: 1. plans and specifications • preliminary design • intermediate design • prefinal/final design • estimated cost • correlation of plans and specifications • selection of appropriate RCRA facilities • compliance with requirements of other environmental laws • equipment startup and operator training 2. additional studies 3. operation and maintenance plan 4. QAPP 5. site safety plan	No Direct Correlation	Corrective Measures Implementation Design, construct, operate, maintain, and monitor the performance of the corrective measures selected in the corrective measures study. Consists of four activities: 1. corrective measures implementation program plan 2. corrective measures design • design plans and specifications • operations and maintenance plan • cost estimate • schedule • construction quality assurance objectives • health and safety plan • design phases 3. corrective measures construction (includes a construction quality assurance program) 4. reporting

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA CORRECTIVE ACTION PROCESS
Final Status Survey Performed to demonstrate that residual radioactive material in each survey unit meets the release criteria.	Long-Term Remedial Assessment Closure/Postclosure NPL Delisting	Post-Removal Site Control Those activities that are necessary to sustain the integrity of a removal action following its conclusion.	Closure/Postclosure

Table F-2 Data Elements for Site Assessments[1]

Data Elements Common to Remedial and Removal Assessment	Generally Remedial Site Assessment Only	Generally Removal Site Assessment Only
• Current human exposure identification • Sources identification, including locations, sizes, volumes • Information on substances present • Labels on drums and containers • Containment evaluation • Evidence of releases (e.g., stained soils) • Locations of wells on site and in the immediate vicinity • Nearby wetlands identification • Nearby land uses • Distance measurements or estimates for wells, land uses (residences and schools), surface waters, and wetlands • Public accessibility • Blowing soils and air contaminants • Photo documentation • Site sketch	• Perimeter survey • Number of people within 200 feet • Some sensitive environments • Review all pathways	• Petroleum releases • Fire and explosion threat • Urgency of need for response • Response and treatment alternatives evaluation • Greater emphasis on specific pathways (e.g., direct contact) • Sampling

[1] From EPA 1993a.

Table F-3 Comparison of Sampling Emphasis between Remedial Site Assessment and Removal Site Assessment[1]

Remedial Site Assessment Emphasis	Removal Site Assessment Emphasis
• Attribution to the site • Background samples • Groundwater samples • Grab samples from residential soils • Surface water sediment samples • Hazard Ranking System factors related to surface water sample locations • Fewer samples on average (10–30) than in removal assessment	• Sampling from containers • Physical characteristics of wastes • Treatability and other engineering concerns • Onsite contaminated soils • Composite and grid sampling • Rapid turnaround on analytical services • Field/screening analyses

Remedial Site Assessment Emphasis	Removal Site Assessment Emphasis
• Strategic sampling for Hazard Ranking System • Contract Laboratory Program usage • Full screening organics and inorganics analyses • Definitive analyses • Documentation, including targets and receptors • Computing Hazard Ranking System scores • Standardized reports	• Removal actions led by potentially responsible party • Goal of characterizing site • Focus on National Continency Plan removal action criteria

[1] From EPA 1993a.

APPENDIX G
HISTORICAL SITE ASSESSMENT INFORMATION SOURCES

This appendix lists information sources often useful to site assessment. The lists are organized in two ways:

(1) **Table G-1**, beginning on page G-1, identifies categories of information sources that are listed, with a brief explanation of the information provided by each source. A contact is provided for additional information. The categories are—

(2) **Table G-2**, beginning on page G-8, identifies information needs by category and lists information sources for each. The categories are—

More complete listings of site assessment information sources are available in the U.S. Environmental Protection Agency's (EPA's) "Site Assessment Information Directory" (EPA 1991b).

Table G-1 Site Assessment Information Sources (Organized by Information Source)

Databases	
Source:	Superfund Enterprise Management System (SEMS)
Provides:	EPA inventory of potential hazardous waste sites. Provides site name, EPA identification number, site address, and the date and types of previous investigations.
Supports:	General site information.
Contact:	U.S. Environmental Protection Agency Office of Land and Emergency Management https://enviro.epa.gov/envirofacts/sems/search
Source:	Records of Decision System (RODS)
Provides:	Information on technology justification, site history, community participation, enforcement activities, site characteristics, scope and role of response action, and remedy.
Supports:	General site information and source and waste characteristics.
Contact:	EPA Office of Land and Emergency Management https://www.epa.gov/superfund/search-superfund-decision-documents

Databases (continued)

Source:	Envirofacts
Provides:	EPA inventory of hazardous waste generators. Contains facility name, address, phone number, and contact name; EPA identification number; treatment, storage, and disposal history; and date of notification.
Supports:	General site information and source and waste characteristics.
Contact:	EPA Office of Land and Emergency Management https://enviro.epa.gov
Source:	WellFax
Provides:	National Water Well Association's inventory of municipal and community water supplies. Identifies public and private wells within specified distances around a point location and the number of households served by each.
Supports:	Groundwater use and characteristics.
Contact:	National Ground Water Association 601 Dempsey Road Westerville, OH 43081 https://www.ngwa.org/about/Contact-NGWA
Source:	Water Quality Portal (WQP)
Provides:	EPA repository of water quality data for waterways within the United States. Can perform a broad range of reporting, statistical analysis, and graphics functions.
Supports:	Geographic and descriptive information on various waterways; analytical data from surface water, fish tissue, and sediment samples; and stream flow data.
Contact:	EPA Office of Water Office of Wetlands, Oceans, and Watersheds https://www.waterqualitydata.us/
Source:	U.S. Geological Survey (USGS) Water Data for the Nation
Provides:	USGS National Water Data Storage and Retrieval System. Administered by the Water Resources Division and contains the Ground Water Site Inventory file. This provides physical, hydrologic, and geologic data about test holes, springs, tunnels, drains, ponds, other excavations, and outcrops.
Supports:	General site information, groundwater use and characteristics, and surface water use and characteristics.
Contact:	USGS Water Resources https://waterdata.usgs.gov/nwis
Source:	RadNet
Provides:	A direct assessment of the population intake of radioactive pollutants due to fallout, data for developing dose computational models, population exposures from routine and accidental releases of radioactive material from major sources, data for indicating additional measurement needs or other actions required in the event of a major release of radioactive material in the environment, and a reference for data comparison with other localized and limited monitoring programs.
Supports:	Source and waste characteristics.
Contact:	EPA National Analytical Radiation Environmental Laboratory http://www.epa.gov/radnet/
Source:	U.S. Department of Defense (DoD) Environment, Safety & Occupational Health Network and Information Exchange (DENIX)
Provides:	Inventory databases for the Formerly Used Defense Sites, Defense Environmental Restoration Program, and Military Munitions Response Program.
Supports:	Site histories and processes, previous remedial activities, and current remediation status.
Contact:	DENIX https://www.denix.osd.mil/

Databases (continued)

Source:	U.S. Nuclear Regulatory Commission (NRC) Agencywide Documents Access and Management System (ADAMS)
Provides:	Documents.
Supports:	Site operating histories, previous removal and remedial activities, ongoing licensed facility documents, and NRC guidance.
Contact:	NRC ADAMS https://www.nrc.gov/reading-rm/adams.html
Source:	U.S. Department of Energy (DOE), Office of Legacy Management
Provides:	Documents
Supports:	DOE postclosure responsibilities to ensure the future protection of human health and the environment.
Contact:	DOE Office of Legacy Management https://www.energy.gov/lm/office-legacy-management

Maps and Aerial Photographs

Source:	U.S. Topo: Maps for America
Provides:	Maps detailing topographic, geographic, political, and cultural features.
Supports:	Site location and environmental setting; latitude/longitude; houses, schools, and other buildings; distances to targets; surface water body types; drainage routes; wetlands and sensitive environments; and karst terrain features.
Contacts:	USGS National Geospatial Program https://www.usgs.gov/the-national-map-data-delivery/topographic-map-access-points
Source:	National Wetlands Inventory Maps
Provides:	Maps delineating boundaries and acreage of wetlands.
Supports:	Environmental setting and wetlands locations.
Contact:	USGS or U.S. Fish and Wildlife Service https://www.fws.gov/program/national-wetlands-inventory/wetlands-mapper
Source:	Flood Insurance Rate Map (FIRM)
Provides:	Maps delineating flood hazard boundaries for flood insurance purposes.
Supports:	Flood frequency.
Contact:	Federal Emergency Management Agency or Local Zoning and Planning Office Federal Insurance Administration Office of Risk Assessment 500 C Street, SW Washington, DC 20472
Source:	State Department of Transportation Maps
Provides:	State maps detailing road systems, surface water systems, and other geographical, cultural, and political features.
Supports:	Site location and environmental setting and distances to targets, wetlands, and sensitive environments.
Contact:	State or local government agency
Source:	National Geologic Map Database
Provides:	Maps detailing surficial exposure and outcrop of formations for interpreting subsurface geology. Bedrock maps describe depth and lateral distribution of bedrock.
Supports:	General stratigraphy beneath and surrounding the site.
Contact:	USGS National Cooperative Geologic Mapping Program https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html

Maps and Aerial Photographs (continued)

Source:	Aerial Photographs
Provides:	Black and white and color photographic images detailing topographic, physical, and cultural features.
Supports:	Site location and size, location and extent of waste sources, identification of surrounding surficial geology, distances to targets, and wetlands and sensitive environments. May provide information on historical site operations, waste quantity, and waste handling practices.
Contact:	State department of transportation Local zoning and planning office County tax assessor's office Colleges and universities (geology or geography departments) EPA Environmental Photographic Interpretation Center (EPIC) U.S. Army Corps of Engineers U.S. Department of Agriculture, U.S. Forest Service USGS DOE NRC U.S. Department of the Interior (and Bureaus)
Source:	EarthExplorer
Provides:	An interactive computer system with information about the Earth's land surfaces. Supports searches of satellite, aircraft, and other remote sensing inventories through interactive and text-based query capabilities.
Supports:	Site location and environmental setting; latitude/longitude; houses, schools, and other buildings; distances to targets; surface water body types; drainage routes; wetlands and sensitive environments; and karst terrain features.
Contact:	USGS National Geospatial Program https://earthexplorer.usgs.gov
Source:	Topologically Integrated Geographic Encoding and Referencing (TIGER) System
Provides:	Automates the mapping and related geographic activities required to support the decennial census and sample survey programs of the U.S. Census Bureau starting with the 1990 decennial census. The topological structure of the TIGER database defines the location and relationship of streets, rivers, railroads, and other features to each other and to the numerous geographic entities for which the Census Bureau tabulates data from its censuses and sample surveys.
Supports:	General site information, soil exposure characteristics, and air pathway characteristics.
Contacts:	Public Information Office Room 2705, FB-3 Census Bureau U.S. Department of Commerce Washington, DC 20233 https://tigerweb.geo.census.gov/tigerweb

Files

Source:	Office Project Files
Provides:	Site investigation reports, logbooks, telecons, references, etc.
Supports:	Information on nearby sites such as town populations, public and private water supplies, well locations, targets, and general stratigraphy descriptions.
Source:	Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Administrative Records
Provides:	Site investigation reports, memoranda for sites subject to CERCLA actions.
Supports:	Information on all phases of the CERCLA process at a specific site, from preliminary assessment to closure (depending on the stage of remediation at the site).
Source:	Resource Conservation and Recovery Act (RCRA) Administrative Records
Provides:	Site history information, potential sources of residual radioactivity and chemical contamination, and information on RCRA corrective actions.
Supports:	Information on facilities that hold RCRA storage and disposal facility permits.
Source:	State Environmental Agency Files
Provides:	Historical site information, permits, violations, and notifications.
Supports:	General site information and operational history, source descriptions, waste quantities, and waste handling practices. May provide results of previous site investigations.
Source:	EPA Regional Libraries
Provides:	Historical information on Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS) (now Superfund Enterprise Management System [SEMS]) sites, permits, violations, and notifications. Provides interlibrary loan services.
Supports:	General site information and operational history, source descriptions, waste quantities, and waste handling practices. May provide results of previous site investigations.
Contact:	USEPA Region 1 Library 5 Post Office Square Suite 100 LIB01-2 Boston, MA 02109-3912 617-918-1990 USEPA Region 2 Library 290 Broadway 23rd Floor New York, NY 10007-1866 212-637-3185 USEPA Region 3 Library (3MD13) 1600 John F. Kennedy Blvd. Philadelphia, PA 19103 215-814-5254 USEPA Region 4 Library 26 W. Martin Luther King Drive Room 406 Cincinnati, OH 45268 513-569-7703
	USEPA Region 5 Library 77 W. Jackson Blvd. Metcalfe Federal Building, 16th Floor Chicago, IL 60604-3590 312-886-6822 USEPA Region 6 Library 1201 Elm Street, Suite 500 Renaissance Tower Dallas, TX 75270 214-655-6424 USEPA Region 7 Library 109 T.W. Alexander Drive Room C261 Research Triangle Park, NC 27711 919-541-2777 USEPA Region 8 Technical Library 1595 Wynkoop Street, 8MSD/IMI Denver, CO 80202-1129 303-312-7226

Files (continued)

USEPA Region 9 Environmental Information Center/Library 75 Hawthorne Street San Francisco, CA 94105 415-947-4406	USEPA Region 10 Library 1200 Sixth Avenue Suite 155, MSD 1 K-03 Seattle, WA 98101 206-553-1289

Experts and Other Sources

Source:	USGS
Provides:	Geologic, hydrogeologic, and hydraulic information, including maps, reports, studies, and databases.
Supports:	General stratigraphy descriptions, karst terrain, depth to aquifer, stream flow, and groundwater and surface water use and characteristics.
Contact:	U.S. Geological Survey or USGS Regional or Field Office 12201 Sunrise Valley Drive Reston, VA 20192
Source:	U.S. Army Corps of Engineers
Provides:	Records and data on engineering projects involving surface waters.
Supports:	Groundwater and surface water characteristics, stream flow, and locations of wetlands and sensitive environments.
Contact:	U.S. Army Corps of Engineers or District Office 441 G Street NW Washington, DC 20314
Source:	State Geological Survey
Provides:	State-specific geologic and hydrogeologic information, including maps, reports, studies, and databases.
Supports:	General stratigraphy descriptions, karst terrain, depth to aquifer, and groundwater use and characteristics.
Contact:	State Geological Survey (local or field office)
Source:	Natural Heritage Program
Provides:	Information on Federal- and State-designated endangered and threatened plants, animals, and natural communities. Maps, lists, and general information may be available.
Supports:	Location of sensitive environments and wetlands.
Contact:	State Environmental Agency
Source:	U.S. Fish and Wildlife Service
Provides:	Environmental information.
Supports:	Locations of sensitive environments, wetlands, and fisheries; and surface water characteristics and stream flow.
Contact:	U.S. Fish and Wildlife Service or U.S. Fish and Wildlife Service 1849 C Street, NW Regional Office Washington, DC 20240
Source:	Local Fish and Wildlife Officials
Provides:	Local environmental information.
Supports:	Locations of sensitive environments, wetlands, and fisheries; and surface water characteristics and stream flow.
Contact:	State or local environmental agency State or local game or conservation office

Experts and Other Sources (continued)	
Source:	Local Tax Assessor or Local Court Records
Provides:	Past and present land ownership records, lot and building sizes, and assessors' maps. May also provide historical aerial photographs.
Supports:	Name of present and past owners/operators, years of ownership, size of site, and operational history.
Contact:	Local town government office
Source:	Local Water Authority
Provides:	Public and private water supply information, including service area maps, well locations and depths, well logs, surface water intake locations, and information on water supply contamination.
Supports:	Locations and populations served by municipal and private drinking water sources (wells and surface water intakes), pumpage and production, blended systems, depth to aquifer, general stratigraphic descriptions, groundwater and surface water characteristics, and stream flow.
Contact:	Local town government office
Source:	Mineral Lease Records
Provides:	Information on possible mining activity, radionuclides of concern, and possible background or reference area information.
Supports:	Historical site activities, residual radionuclides of interest, and possible chemical contamination associated with ore extraction activities.
Contact:	Local town government office
Source:	Local Health Department
Provides:	Information and reports on health-related problems that may be associated with a site. Information on private and municipal water supplies and onsite monitoring wells.
Supports:	Primary/secondary targets differentiation and locations and characteristics of substances present at the site.
Contact:	Local town government office
Source:	Local Zoning Board or Planning Commission
Provides:	Records of local land development, including historical land use and ownership, and general stratigraphy descriptions.
Supports:	General site description and history, previous ownership, and land use.
Contact:	Local town government office
Source:	Local Fire Department
Provides:	Records of underground storage tanks in the area, safety data sheets for local commercial and industrial businesses, and other information on hazardous substances used by those businesses.
Supports:	Location and use of underground storage tanks and other potential sources of hazardous substances, and identification of hazardous substances present at the site.
Contact:	Local town government office
Source:	Local Well Drillers
Provides:	Public and private water supply information, including well locations and depths, well logs, pumpage, and production.
Supports:	Populations served by private and municipal drinking water wells, depth to aquifer, and general stratigraphic information.

Experts and Other Sources (continued)	
Source:	Local University or College
Provides:	Geology/environmental studies departments with potentially relevant published materials (reports, theses, dissertations) and faculty experts knowledgeable in local geologic, hydrologic, and environmental conditions.
Supports:	General stratigraphic information, groundwater and surface water use and characteristics, and stream flow.
Source:	Site Reconnaissance
Provides:	Onsite and offsite visual observation of the site and surrounding area.
Supports:	General site information; source identification and descriptions; general groundwater, surface water, soil, and air pathway characteristics; nearby targets; and probable point of entry to surface water.

Table G-2 Site Assessment Information Sources (Organized by Information Needed)

General Site Information

Site Location, Latitude/Longitude
SEMS
U.S. Topo: Maps for America
State Department of Transportation Maps
Site Reconnaissance
EarthExplorer
U.S. Census Bureau TIGER Mapping Services
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
RODS

Type of Operation and Site Status
EPA Regional Libraries
State Environmental Agency Files
Site Reconnaissance
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records

Owner/Operator Information
EPA Regional Libraries
State Environmental Agency Files
Local Tax Assessor
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records

Environmental Setting, Size of Site
U.S. Topo: Maps for America
Aerial Photographs
Site Reconnaissance
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records

Source and Waste Characteristics

Source Types, Locations, Sizes
EPA Regional Libraries
State Environmental Agency Files
Aerial Photographs
Site Reconnaissance
DOE Field Offices
CERCLA and RCRA Administrative Records
NRC Agreement State Licensing Records
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records

Hazardous Substances Present
EPA Regional Libraries
State Environmental Agency Files
Envirofacts
Local Health Department
Local Fire Department
RadNet
Local Public Works Department
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
CERCLA and RCRA Administrative Records

Source and Waste Characteristics (continued)

Waste Types and Quantities
EPA Regional Office Files
State Environmental Agency Files
Envirofacts
Local Fire Department
Aerial Photographs
Site Reconnaissance
Aerial Radiation Surveys
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Groundwater Use and Characteristics

General Stratigraphy
USGS Topographic Maps
USGS
State Geological Surveys
Geologic and Bedrock Maps
Local Experts
Local University or College
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Private and Municipal Wells
Local Water Authority
Local Health Department
Local Well Drillers
State Environmental Agency Files
National Ground Water Association WellFax
USGS Water Data for the Nation
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Karst Terrain
U.S. Topo: Maps for America
USGS
State Geological Surveys
Geologic and Bedrock Maps
Local Experts
Local University or College
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Distance to Nearest Drinking Water Well
U.S. Topo: Maps for America
Local Water Authority
Local Well Drillers
Local Health Department
National Ground Water Association WellFax
USGS Water Data for the Nation
Site Reconnaissance
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Depth to Aquifer
USGS
State Geological Surveys
Geologic and Bedrock Maps
Local Experts
Local Well Drillers
USGS Water Data for the Nation
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Wellhead Protection Areas
State Environmental Agency
Local Water Authority
Local Well Drillers
Local Health Department
EPA Regional Water Officials
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Surface Water Use and Characteristics

Surface Water Body Types
U.S. Topo: Maps for America
State Department of Transportation Maps
Aerial Photographs
Site Reconnaissance
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Drinking Water Intakes
Local Water Authority
U.S. Topo: Maps for America
U.S. Army Corps of Engineers
State Environmental Agency
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records

Distance to Nearest Surface Water Body
U.S. Topo: Maps for America
State Department of Transportation Maps
Aerial Photographs
Site Reconnaissance
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Fisheries
U.S. Fish and Wildlife Service
State Environmental Agency
Local Fish and Wildlife Officials
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records

Surface Water Flow Characteristics
USGS
State Environmental Agency
U.S. Army Corps of Engineers
WQP
USGS Water Data for the Nation
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Locations of Sensitive Environments
U.S. Topo: Maps for America
State Department of Transportation Maps
State Environmental Agency
U.S. Fish and Wildlife Service
Local Fish and Wildlife Officials
National Wetlands Inventory Maps
Ecological Inventory Maps
Natural Heritage Program
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records
U.S. Army Corps of Engineers

Flood Frequency at the Site
Federal Emergency Management Agency
State Environmental Agency

Soil Exposure Characteristics

Number of People Living Within 200 Feet
Site Reconnaissance
U.S. Topo: Maps for America
Aerial Photographs
U.S. Census Bureau TIGER Mapping Service

Schools or Day Cares Within 200 Feet
Site Reconnaissance
U.S. Topo: Maps for America
Local Street Maps

Number of Workers On Site
Site Reconnaissance
Owner/Operator Interviews
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records

Locations of Sensitive Environment
U.S. Topo: Maps for America
State Department of Transportation Maps
State Environmental Agency
U.S. Fish and Wildlife Service
Ecological Inventory Maps
Natural Heritage Program
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records
Mineral Lease Records
CERCLA and RCRA Administrative Records

Air Pathway Characteristics

Populations within 4 Miles
U.S. Topo: Maps for America
Site Reconnaissance
U.S. Census Bureau TIGER Mapping Services
NRC or Agreement State Records
DoD Facility Records
DOE Facility Records

Locations of Sensitive Environments, Acreage of Wetlands
U.S. Topo: Maps for America
State Department of Transportation Maps
State Environmental Agency
U.S. Fish and Wildlife Service
National Wetlands Inventory Maps
Ecological Inventory Maps
Natural Heritage Program

Distance to Nearest Individual
U.S. Topo: Maps for America
Site Reconnaissance

APPENDIX H
DESCRIPTION OF FIELD SURVEY AND LABORATORY ANALYSIS EQUIPMENT

H.1 Introduction

This appendix provides information on various types of field and laboratory equipment used to measure radiation levels and radioactive material concentrations. The descriptions offer general guidance, and those interested in purchasing or using the equipment are encouraged to contact vendors, health physics professionals, and technologists for specific information and recommendations. Although most of the equipment described in this appendix is in common use, a few specialty items are included to demonstrate promising developments.

The equipment is divided into two broad groupings—field survey equipment and laboratory instruments—and each group is subdivided into radiation (alpha, beta, gamma, etc.) or detection (mobile detection arrays, dosimeters, etc.) categories. For each system discussed, this appendix offers one or two pages of information, including type of use (field or laboratory), the primary and secondary radiation detected, applicability for site surveys, operation, specificity/sensitivity, and efficiency.

The Applicability to Site Surveys sections discuss how the equipment is most useful for performing site radiological surveys. The Operation sections provide basic technical information on what each system includes, how it works, its practical use in the field, and its features. The Specificity/Sensitivity sections address each system's strengths, weaknesses, and the concentrations of radioactive material it can measure.

It is assumed that the user of this appendix has a basic familiarity with radiological field and laboratory detection equipment. Some of the typical instrument features and terms are listed below and may not be described separately for the individual instruments:

- *Field survey equipment:* Field survey equipment consists of a detector, a survey meter (electronics, power source), and interconnected cables, although these are sometimes packaged in a single container.
  - **The detector or probe** is the portion that is sensitive to radiation. The probe is designed with materials that are operated at various voltages, making that probe sensitive to one or more types of radiation. Some detectors feature a window or a shield whose construction material and thickness make the detector more or less sensitive to a particular radiation. The size of the detector can vary depending on the specific need, but it is often limited by the characteristics of the construction materials and the physics of the detection process.
  - **The survey meter** provides high voltage through a power source (batteries) to the detector and contains the electronics that process the detector's signal. The survey meter displays the readings in analog or digital fashion. An analog survey meter has a continuous swing needle and typically a manually operated scale switch, which is used to keep the needle on scale. A digital survey meter displays the reading as a number, typically on a liquid crystal display (LCD) screen. The scaling switch may not be required on digital survey meters as they have an automatic scaling system.

- **The interconnecting cables** serve to transfer the high-voltage and detector signals. These cables may be inside those units that combine the meter and detector into a single box, but they are often external and connect the detector and the survey meter in a way that allows the user to interchange detectors or probes. Older systems require turning off the meter before switching cables (detectors). Newer systems do not, and users can switch the probes at any time—a process called a “hot swap.” Some instruments might be equipped with Bluetooth™ connections, which allow probes to transmit data signals to the receptors, such as Bluetooth™-equipped computers, phones, or tablets.

- *Scanning and measuring surveys:* In a scanning survey, the field survey meter is operated while the detector is moving over an area to search for a change in readings. Because the meter’s audible signal responds faster than the meter display, listening to the built-in speaker or using headphones allows the user to more quickly discern changes in radiation level. When a scanning survey detects a change, the meter can be held in place for a more accurate static measurement.

- *Integrated readings:* When a lower detection level is desired, the reading can be integrated using internal electronics or an external scaler to give total values over time. The degree to which the detection capability can be improved depends largely on the integration time selected.

- *Units of measure:* Survey meters with conventional meter faces measure radiation levels in units of counts, milliroentgen (mR), microroentgen (µR), millirad (mrad), or millirem (mrem) per unit of time (e.g., counts per minute [cpm], mR/hour [h], or µR/h). Those with International System meter faces use units of millisievert (mSv), microsievert (µSv), or milligray (mGy) per unit of time (e.g., mSv/h, µSv/h, or mGy/h).

Tables H-2–**H-8** at the end of the appendix summarize the description and application of the various measurement methods.

H.2 Field Survey Equipment

H.2.1 Alpha Particle Detectors

System: Alpha-Beta Scintillation Survey Meter
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Alpha ***Secondary:*** Beta (alpha-beta survey meter only)

Applicability to Site Surveys: The alpha scintillation survey meter is useful for determining the presence or absence of alpha-emitting radioactive material on nonporous surfaces, swipes, and air filters, or on irregular surfaces if the degree of surface shielding is known.

Operation: This survey meter uses an alpha radiation detector with a window of <1 milligram (mg)/square centimeter (cm^2) and a sensitive area of approximately 50–100 cm^2 (8–16 square inches [$in.^2$]). The detector has a thin, aluminized window of Mylar™ that blocks ambient light but allows alpha radiation to pass through. The detecting medium is silver-activated zinc sulfide (ZnS(Ag)). Radiation incident to the detecting medium creates pulses of light. Light pulses are amplified by a photomultiplier tube (PMT) and passed to the survey meter. When the discriminator is appropriately adjusted, the meter is sensitive primarily to alpha radiation. Newer alpha/beta survey meters incorporate the ZnS(Ag) detection medium, adhered to a plastic scintillator that is approximately 0.25 millimeter (mm) (0.01 inch [in.]) thick to provide both alpha and beta detection capability in one survey meter. The probe is generally placed close to the surface because of the short range of alpha particles in air. A scanning survey is used to identify areas of elevated concentrations of radioactive materials on surfaces, followed by a direct survey to obtain actual measurements. Integrating the readings over time improves the detection level enough to make the instrument very useful for alpha (and beta, if applicable) measurements of concentrations of radioactive material on surfaces for many radionuclides. The readings are displayed in cpm, but factors can usually be obtained to convert readings from cpm to disintegrations per minute (dpm) by knowing the proper efficiency of the detector. Conversion factors can be adversely affected by the short range of alpha particles (less so for beta particles, which are shielded to often uncertain degrees if they are embedded in the surface). Meters typically use two to six C- or D-cell batteries and will operate for 100–300 hours.

Specificity/Sensitivity: When the discriminator is correctly adjusted, the alpha survey meter measures primarily alpha radiation, and the alpha-beta survey meter will distinguish between both radiations, even in a mixed radiation field. A scanning survey gives a quick indication of the presence or absence of radioactive material on surfaces, and integrating the readings provides a measure of the activity on a surface, swipe, or filter. Irregular, porous, moist, or painted surfaces easily absorb alpha radiation; this should[1] be carefully considered when converting count rate data to concentrations of radioactive material on surfaces. The minimum detection level is approximately 10 cpm using the needle deflection or 1–2 cpm when using headphones or a scaler. Meters typically provide adjustable audio divide (e.g., one event per click, 10 events per click), so the product manual should be consulted to preclude underestimating the concentration of radioactive material.

[1] The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

System: Gas-Flow Proportional Counter
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Alpha, beta ***Secondary:*** Gamma

Applicability to Site Surveys: This equipment measures gross concentrations of radioactive material emitting alpha or beta/gamma radiation on relatively flat surfaces, such as the floors and walls of facilities. It also serves as a screen to determine whether more nuclide-specific analyses may be needed.

Operation: This system consists of an air- or gas-flow proportional detector, gas supply, supporting electronics, and a scaler or rate meter. Small detectors (~50–100 cm^2 open probe face area) are hand held, and larger detectors (e.g., 600 cm^2) are mounted on a rolling cart. The detector entrance window can be <1 mg/cm^2 to almost 10 mg/cm^2, depending on whether alpha, alpha-beta, or gamma radiation is monitored. The gas-flow proportional detector normally uses P-10, a mixture of 10 percent methane and 90 percent argon. The detector is positioned as close as practical to the surface being monitored for good counting efficiency without risking damage from the detector touching the surface. Quick-disconnect fittings allow the system to be disconnected from the gas bottle for hours with little loss of counting efficiency. The detector's operating voltage can be set to make it sensitive only to alpha radiation, to both alpha and beta radiation, or to beta and low-energy gamma radiation. These voltages are determined for each system by placing either an alpha source (e.g., thorium-230 [^{230}Th] or americium-241 [^{241}Am]) or a beta source (e.g., strontium-90 [^{90}Sr]) that is both facing and near the detector window, then increasing the high voltage in incremental steps until the count rate becomes constant. The alpha plateau—the region of constant count rate—will be almost flat. The beta plateau will have a slope of 5–15 percent per 100 volts (V). Operation on the beta plateau allows detection of some gamma radiation, but the efficiency is very low. Some systems use a spectrometer to separate alpha events from beta and gamma events, allowing simultaneous determination of both the alpha and combined beta/gamma concentrations of radioactive material on surfaces.

Specificity/Sensitivity: These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radionuclides. Background for operation on the alpha plateau is very low (2–3 cpm), which is still higher than for laboratory detectors because of the larger detector size of the field instrument. Background for operation on the beta plateau is dependent on the ambient gamma and cosmic ray background and typically ranges from 100 to several hundred cpm. Typical instrument efficiencies for unattenuated alpha sources are 15–20 percent. Beta efficiency depends on the window thickness and the beta energy. For ^{90}Sr/yttrium-90 (^{90}Y) in equilibrium, instrument efficiencies range from 5 percent for highly attenuated to about 35 percent for unattenuated sources. Typical gamma ray instrument efficiency is less than 1 percent. The presence of natural radionuclides in the surfaces could interfere with the detection of other radionuclides. Unless the nature of the residual radioactive material and any naturally occurring radionuclides is well known, this system is better used for assessing gross surface concentrations of radioactive material. The texture and porosity of the surface can hide or shield radioactive material from the detector, causing levels to be underestimated. Changes in temperature can affect the detector's sensitivity. Incomplete flushing with gas can cause a nonuniform response over the detector's surface. Condensation in the gas lines or use of the quick-disconnect fittings can cause count rate instability.

System: Geiger-Mueller Survey Meter with Beta Pancake Probe
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Beta ***Secondary:*** Gamma, alpha

Applicability to Site Surveys: This instrument is used to find and measure low concentrations of radioactive material emitting beta or gamma radiation on relatively flat surfaces.

Operation: This instrument consists of a flat "pancake" type Geiger-Mueller (GM) detector connected to a survey meter that measures radiation response in cpm. It has a thin 1.4 mg/cm^2 window detector and a probe area of 10–100 cm^2. The detector housing is typically a rigid metal (e.g., steel, aluminum, lead, or tungsten) on all sides, except the radiation entrance face or window, which is made of mica, Mylar™, or similar material, giving the detector a directional response. The detector requires approximately 900 V for operation. It is held within a few centimeters of the surface to minimize the thickness of air shielding in between the radioactive material and the detector. It is moved slowly to scan the surface in search of elevated readings, then held in place long enough to obtain a stable measurement. Radiation entering the detector ionizes the gas, causes a discharge throughout the entire tube, and results in a single count being sent to the meter. The meter reading in cpm is converted to a beta surface activity concentration in the range of 1,700 becquerels (Bq)/m^2 (1,000 dpm/100 cm^2) using isotope-specific factors.

Specificity/Sensitivity: Pancake-type GM detectors primarily measure beta count rate in close contact with surfaces to indicate the presence of radioactive material, but they are also sensitive to any gamma or alpha radiation that enters the detector and causes ionization. As a result, they cannot determine the type or energy of that radiation, except by using a set of absorbers. To be detected, beta particles must have enough energy to penetrate any surface material that the radioactive material is absorbed in, the detector window, and the layer of air and other shielding materials in between. Low-energy beta particles from emitters such as hydrogen-3 (^{3}H) (tritium), which emits a maximum energy of 18.6 kiloelectron volts (keV), cannot penetrate the window and are not detectable, but higher energy betas, such as those from cobalt-60 (^{60}Co), which emits a 314 keV beta particle, can be readily detected. The beta detection total efficiency at a field site is primarily a function of the beta energy, window thickness, and surface condition. The detection capability can be improved by using headphones or the audible response during scans, by integrating the count rate over a longer period, or by counting the removable radioactive material collected on a smear. The nominal approximately 5 cm (2 in.) diameter detector can measure an increase of about 100 cpm above background, which equates to 4,200 Bq/m^2 (2,500 dpm/100 cm^2) of ^{60}Co on a surface under the detector or 20 Bq (500 picocuries [pCi]) on a swipe. Larger 100 cm^2 detectors improve detection level and eliminate the need to swipe. The sensitivity to gamma radiation is about 10 percent or less of the beta sensitivity, but the instrument alpha detection efficiency is difficult to evaluate.

H.2.2 Gamma Ray Detectors

System: Hand-Held Unpressurized Ion Chamber Survey Meter
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** Beta (with beta shield)

Applicability to Site Surveys: The hand-held ion chamber survey meter measures the true gamma radiation exposure rate, in contrast to most other survey meter/probe combinations, which are calibrated to measure exposure rate at one energy and approximate the exposure rate at all other energies. Because of their high detection limit, these instruments are not applicable for many final status surveys (FSSs). Some hand-held ion chambers include a sliding shield used for beta detection. The shield protects a thin Mylar™ film, allowing beta particles to enter the ion chamber for detection.

Operation: This device uses an ion chamber operated at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to generate secondary ion pairs as a proportional counter does. The readout is in units of mR/h or some multiple of mR/h. If equipped with an integrating mode, the operator can measure the total exposure over a period of time. The instrument may operate on two D-cell batteries or a 9 V battery that will last for 100–200 hours of operation.

Specificity/Sensitivity: Sealed ion chamber instruments respond only to gamma or x-radiation. They have no means to identify radionuclides. Typical ion chamber instruments have a lower limit of detection of 0.5 mR/h. These instruments can display readings below this, but the readings may be erratic and have large errors associated with them. In integrate mode, the instrument detection level can be as low as 0.05 mR/h.

System: Hand-Held Pressurized Ionization Chamber Survey Meter
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** None

Applicability to Site Surveys: The hand-held pressurized ionization chamber (PIC) survey meter measures the true gamma radiation exposure rate, in contrast to most other survey meter/probe combinations, which are calibrated to measure exposure rate at one energy and approximate the exposure rate at all other energies. Because of their high detection limit, these instruments in a rate mode of operation have limited applicability for many FSSs; however, operation in integrate mode improves detection capability.

Operation: This device uses a pressurized air ion chamber operated at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to cause secondary ionization. The instrument is identical to the ion chamber meter on the previous page, except in this case, the ion chamber is sealed and pressurized to 2–3 atmospheres to improve the detection capability of the instrument by the same factor. The units of readout are µR/h or mR/h. A digital meter will allow an operator to integrate the total exposure over a period of time.

Specificity/Sensitivity: Because the ion chamber is sealed, PIC instruments respond only to gamma or x-ray radiation. They have no means to provide the identity of radionuclides. Typical instruments have a lower limit of detection of 0.1 mR/h, or as low as 0.01 mR in integrate mode. These instruments can display readings below this, but the readings may be erratic and have large errors associated with them.

System: Pressurized Ionization Chamber
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Moderate- to high-energy gamma ***Secondary:*** None

Applicability to Site Surveys: The PIC is a highly accurate ionization chamber for measuring gamma exposure rate in air and for correcting for the energy dependence of other instruments due to their energy sensitivities. It is excellent for routine monitoring of general areas based on exposure rate, as well as for cross-calibrating other energy-dependent field instruments to obtain more accurate results when characterizing and evaluating the effectiveness of remediation of sites affected by residual radioactive material based on exposure rate. However, most sites also require nuclide-specific identification of the contributing radionuclides. Under these circumstances, PICs must be used in conjunction with other soil sampling or spectrometry techniques to evaluate the success of remediation efforts.

Operation: The PIC detector is a large sphere of compressed argon-nitrogen gas at 10–40 atmospheres of pressure surrounded by a protective box. The detector is normally mounted on a tripod and positioned to sit about 3 feet (ft) off the ground. It is connected to an electronics package in which a strip chart recorder or digital integrator measures instantaneous and integrated exposure rate. It operates at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to amplify or increase the number of ion pairs. The high pressure inside the detector and the integrate feature make the PIC much more sensitive and precise than other ion chambers for measuring low exposures. The average exposure rate is calculated from the integrated exposure and the operating time. Arrays of PIC systems can be linked by telecommunications so that their data can be observed remotely.

Specificity/Sensitivity: The PIC measures gamma or x-ray radiation and cosmic radiation. It is highly stable, relatively energy independent for energies above 80 keV, and serves as an excellent tool to calibrate other survey equipment in the field to measure exposure rate. Because the PIC is normally uncollimated, it measures cosmic, terrestrial, and foreign source contributions without discrimination. Its rugged and stable behavior makes it an excellent choice for an unattended sensor where area monitors for gamma emitters are needed. PICs are highly sensitive, precise, and accurate to vast changes in exposure rate (1–10 roentgen [R]/h), one of its major advantages. PICs lack any ability to distinguish either energy spectral characteristics or source type. If sufficient background information is obtained, the data can be processed using algorithms that employ time and frequency domain analysis of the recorded systems to effectively separate terrestrial, cosmic, and “foreign” source contributions.

System: Survey Meter with Geiger-Mueller Gamma Probe
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** Beta

Applicability to Site Surveys: This instrument is used to give a quick indication of gamma radiation levels at a site. Because of its high detection limit, the GM gamma survey meter may be useful during characterization surveys, but it may not meet the needs of FSSs.

Operation: This instrument consists of a cylindrical GM detector connected to a survey meter. It is calibrated to measure gamma exposure rate in mR/h. The thick-walled 30 mg/cm^2 detector is surrounded by a protective rigid metal housing. Some units, described as “end window” or “side window,” have a hinged shield or rotating sleeve that opens to expose an entry window of Mylar™, mica, or a similar material, allowing beta radiation to enter the sensitive volume. The detector requires approximately 900 V for operation. It is normally held at waist height, but it is sometimes placed in contact with an item to be evaluated. It is moved slowly over the area to scan for elevated readings; observe the meter; or, preferably, listen to the audible signal. Then it is held in place long enough to obtain a stable measurement. Radiation entering the detector ionizes the gas, causes a discharge throughout the entire tube, and results in a single count being sent to the meter. Count rate is converted to exposure rate at calibration by exposing the detector at discrete levels and adjusting the meter scale(s) to read accordingly. In the field, the exposure rate is read directly from the meter. If the detector housing has an entry window, an increase in the “open-shield” versus “closed-shield” reading indicates the presence of beta radiation, but the difference is not a direct measure of the beta radiation level.

Specificity/Sensitivity: GM meters measure gamma and x-ray radiation, and those with an entry window can identify if the radiation field includes alpha or beta radiation. Because GM detectors are sensitive to any energy of alpha, beta, or gamma radiation that enters the detector, instruments that use these detectors cannot identify the type or energy of that radiation or the specific radionuclides present. The capability can be improved by using headphones or the audible response during scans or by integrating the exposure rate over time. The instrument has two primary limitations for environmental work. First, its minimum detection level is high (about 0.1 mR/h in rate meter mode or 0.01 mR/h in integrate mode). Some instruments use a large detector to improve low-end response. However, in many instances the instrument is not sensitive enough for site survey work. Second, the detector’s energy response is nonlinear. Energy compensated survey meters are commercially available, but the instrument’s response to low-energy gammas may be reduced.

System: Sodium Iodide Survey Meter
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** None

Applicability to Site Surveys: Thallium-activated sodium iodide (NaI[Tl]) (shortened here to NaI) survey meters are useful for determining ambient radiation levels and for estimating the concentration of radioactive materials at a site. They can be response checked against a PIC and then used in its place so that readings can be taken more quickly. When coupled with a multichannel analyzer (MCA), NaI survey meters can be used for gamma spectroscopy.

Operation: The NaI survey meter measures gamma radiation levels in µR/h, mR/h, or cpm. Its response is energy and count rate dependent, so comparison with a PIC necessitates a conversion factor for adjusting the meter readings to true µR/h values. The conversion factor obtained from this comparison is valid only in locations where the radionuclide mix is identical to that where the comparison is performed and over a moderate range of readings. The detector is held at waist level or suspended near the surface and walked through an area while the surveyor listens to the audio, watches the display for changes, or uses data logging mode. Typically, scaler meters are used; however, for fixed measurements with analog meters, the meter is held in place and the response is allowed to stabilize before each measurement is taken, with longer times required for lower responses. Generally, the center of the needle swing or the integrated reading is recorded. The detector is an NaI crystal inside an aluminum container with an optical glass window that is connected to a PMT. A gamma ray that interacts with the crystal produces scintillations that travel out of the crystal and into the PMT. There, electrons are produced and multiplied to create a readily measurable pulse whose magnitude is proportional to the energy of the gamma ray incident on the crystal. Electronic filters accept the pulse as a count if certain discrimination height restrictions are met. This translates into a meter response. Instruments with pulse height discrimination circuitry can be calibrated to view the primary gamma decay energy of an isotope by adjusting the discrimination circuitry to partially tune out other energies. However, this also limits its ability to measure exposure rate.

Specificity/Sensitivity: NaI survey meters measure gamma radiation in µR/h, mR/h, or cpm, with a minimum detection capability of about 1–5 µR/h (200–1,000 cpm) or lower in digital integrate mode. When using the visual display, a reading error of 50 percent can occur at low count rates because of a large needle swing, but this decreases with increased count rate. NaI crystals for hand-held instruments typically vary in size from 2.54 cm (1 in.) x 2.54 cm (1 in.) to 7.62 cm (3 in.) x 7.62 cm (3 in.). The typical instrument used for environmental surveys is 5 cm (2 in.) x 5 cm (2 in.). Each is quite energy sensitive, with the greatest response around a particular energy and decreasing in either direction. Measuring the radiation level at a location with both a PIC and the survey meter gives a factor for converting subsequent readings to actual exposure rates. This ratio can change with location. Some meters have circuitry that looks at a few selected ranges of gamma energies or one at a time with the aid of a single channel analyzer. The detector should be protected against thermal or mechanical shock that can break the NaI crystal or the PMT. Covering at least the crystal end with padding is often sufficient protection.

System: Lanthanum Bromide Survey Meter
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** None

Applicability to Site Surveys: Cerium-activated lanthanum bromide (LaBr:Ce) survey meters (shortened to LaBr meters) are useful for identifying radionuclides and produce semi-quantitative estimates of gamma-emitting isotopes in various media. LaBr offers improved energy resolution as compared to similarly sized NaI survey meters and does not require the supporting infrastructure of high-purity germanium detectors (discussed later in this section). These survey meters allow a more accurate resolution of energy peaks in ranges, as compared to NaI detectors, where isotopes often have many overlapping peaks.

Operation: LaBr survey meters measure gamma radiation levels in µR/h or cpm. Field use of LaBr meters allows identification of difficult-to-determine isotopes, such as by distinguishing between natural and depleted uranium. The detector is held at waist level (dose rate) or suspended (surface measurements) and walked through an area while the surveyor listens to the audio, watches the display, or uses data logging mode. Scaler meters are typically used; however, for fixed measurements, the meter is held in place and the response allowed to stabilize before each measurement is taken, with longer times required for lower responses.

Specificity/Sensitivity: Because of recent advances in growing LaBr scintillation crystals, the available ranges in size are comparable to hand-held NaI crystals and have demonstrated a high light output (~60,000 photons per megaelectron volt [MeV]) with a fast decay time. The response function of LaBr scintillators has been shown to be linear and improves with increased photon energy. The energy resolution of around 3.0 percent at 661 keV makes the resolution of this survey meter about two times better than that of the NaI meter because of the high light output and good homogeneity of the crystals. LaBr crystals have a relatively high intrinsic radiation background (1–2 counts per cubic centimeter per second [counts cm^{-3} s^{-1}]) because of intrinsic activity from lanthanum-138 and actinium-227, leading manufacturers to improve crystal manufacturing and to use algorithms or other background suppression techniques to achieve the suitable detection capability required for detecting and measuring low-activity samples. Thus, the intrinsic photopeak efficiency of LaBr scintillators has been documented to be greater than 20 percent more efficient at moderate energies (~120 keV) to more than 6 percent greater at higher energies (1,333 keV) as compared to similarly sized NaI meters. LaBr is more hygroscopic than NaI, and the detector should be protected against thermal or mechanical shock, which can break the crystal or the PMT.

System: Cadmium Zinc Telluride Detectors
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** None

Applicability to Site Surveys: Cadmium zinc telluride (CZT) detectors are room-temperature semiconductors that are used in systems to identify radionuclides and produce semi-quantitative estimates of activity concentrations of gamma-emitting radionuclides in a variety of media. Currently used primarily in medical, industrial, and homeland security applications, CZT detectors can be modular, offer better spectroscopic resolution than currently available scintillators, and can process more than 10 million photons per second per square millimeter (photons s^{-1} mm^{-2}). Although the detector is not widely used in site surveys at present, the ability to produce CZT detector arrays that operate at room temperatures makes it a potential candidate for wider applications in surveys of soil, buildings, and other materials affected by residual radioactive material.

Operation: CZT detectors are typically fabricated with very thin metalized electrode geometries deposited on the detector surfaces. These electrodes are then electrically biased, creating a difference in electrical potential within the detector volume. When ionizing radiation interacts with the crystal, electron-hole pairs are created and migrate to oppositely charged electrodes. There, they are collected and amplified and produce an electrical signal proportional to the energy of the incoming radiation, which is fed into an MCA to generate gamma-ray spectra. By adding orthogonal strip electrodes on two faces, or an array of pixel electrodes on one face, a single crystal can be segmented into a position-sensitive detector. This position sensitivity allows for the CZT crystal, or an array of CZT crystals, to be incorporated into a gamma-ray imaging device, such as a Compton camera.

Specificity/Sensitivity: The CZT detector is a direct conversion semiconductor with a density of about 5.8 grams (g)/cm^3. Its density and high effective atomic number (Z_{eff}) (~50) give it high stopping power for typical energies of interest. What makes CZT detectors unique is their wide band gap and the sufficiently low amount of energy needed to create an electron/hole pair. The wide band gap allows their use at room temperature, and the energy per electron/hole pair offers much better resolution compared to other gamma detectors that can be operated at room temperatures, such as the widely used NaI detectors. The high value of the atomic number of CZT leads to a high intrinsic photopeak efficiency and a favorable photopeak/Compton ratio, even when the detector volume is relatively small. A negative aspect of CZT is that the mobility and lifetime of the electrons and the holes are quite different. Because of their low mobility and short lifetime, holes are trapped very quickly and cannot contribute to the formation of a full energy signal. Consequently, in a gamma-ray spectrum, the corresponding pulses contribute to a useless continuum below the photopeak or degrade the photopeak resolution by contributing to the low-energy tailing. A second disadvantage of CZT is the difficulty of obtaining large, homogenous single crystals—a precondition for making large-volume detectors. Detector arrays can be constructed to increase the detector volume, but the cost may inhibit wider applications.

System: Portable Germanium Multichannel Analyzer System
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** None

Applicability for Site Surveys: This system, available in liquid-cooled, cryo-cooled, or mechanically cooled variations, produces (1) semi-quantitative concentration estimates of uranium and plutonium in soil, water, and air filters, and (2) quantitative estimates of many other gamma-emitting isotopes. The detector may be used in a vertical orientation to determine, in situ, gamma isotope concentrations in soil.

Operation: This system consists of a portable high-purity germanium detector with cooler, high-voltage power supply, and an MCA. It is used to identify and quantify gamma-emitting isotopes in soil or other surfaces.

Germanium is a semiconductor material. When a gamma ray interacts with a germanium crystal, it produces electron-hole pairs. An electric field is applied that causes the electrons to move in the conduction band and the holes to pass the charge from atom to neighboring atoms. The charge is collected rapidly and is proportional to the deposited energy.

The typical system consists of a built-in or portable MCA weighing about 7–10 pounds with batteries, a special portable low-energy germanium detector with a built-in shield, and the acquisition control and spectrum analysis software. Detectors requiring liquid nitrogen are integrally mounted to a liquid nitrogen dewar. The liquid nitrogen is added 2–4 hours before use and replenished every 4–72 hours based on capacity.

The MCA includes all required front-end electronics, such as a high-voltage power supply, an amplifier, a digital stabilizer, and an analog-to-digital converter, which are fully controllable from a laptop computer and software.

For in situ applications, a collimated detector is positioned at a fixed distance from a surface to provide multichannel spectral data for a defined surface area. It is especially useful for qualitative and (based on careful field calibration or appropriate algorithms) quantitative analysis of freshly deposited radioactive material. Additionally, with prior knowledge of the depth distribution of the primary radionuclides of interest or using algorithms that match the site, the in situ system can be used to estimate the content of radionuclides distributed below the surface (dependent, of course, on adequate detection capability).

Calibration based on Monte Carlo modeling of the assumed source-to-detector geometry or computation of fluence rates with analytical expressions is an important component of the accurate use of field spectrometry when it is not feasible or desirable to use real radioactive sources. Such modeling used in conjunction with field spectrometry is becoming much more common, especially when using the Monte Carlo N-Particle® computer software system.

Specificity/Sensitivity: With proper calibration or algorithms, field spectrometers can identify and quantify concentrations of gamma-emitting radionuclides in the middle-to-upper energy range (i.e., 50 keV with a P-type detector or 10 keV with an N-type detector).

For lower energy photons, as are important for plutonium and americium, an N-type detector or a planar crystal is preferred with a very thin beryllium window. This configuration allows measurement of photons in the energy range 5–80 keV. The beryllium window is quite fragile and is a target of corrosion; it should be protected accordingly.

The detector high voltage should be applied only according to the manufacturer's specifications or when the system has cooled for several hours. These systems can accurately identify plutonium, uranium, and many gamma-emitting isotopes in environmental media, even if a mixture of radionuclides is present. Germanium has an advantage over NaI because it can produce a quantitative estimate of concentrations of multiple radionuclides in such samples as soil, water, and air filters.

A specially designed low-energy germanium detector that exhibits very little deterioration in the resolution as a function of count rate may be used to analyze uranium, plutonium, or other gamma-emitting radionuclides. When the detector is equipped with a built-in shield, it is unnecessary to build complicated shielding arrangements while making field measurements. Tin filters can be used to reduce the count rate from the ^{241}Am 59 keV line, which allows the electronics to process more of the signal coming from plutonium or uranium.

A plutonium content of 10 mg can be detected in a standard 55-gallon waste drum in about 30 minutes, although with high uncertainty. A uranium analysis can be performed for an enrichment range from depleted to 93 percent enrichment. The measurement time can be on the order of minutes, depending on the enrichment and the attenuating materials.

H.2.3 X-Ray and Low-Energy Gamma Detectors

System: FIDLER Probe with Survey Meter
Field/Laboratory: Field
Radiation Detected: ***Primary:*** X-ray ***Secondary:*** Low-energy gamma

Applicability to Site Surveys: The Field Instrument for the Detection of Low-Energy Radiation (FIDLER) probe is a specialized detector optimized to detect gamma and x-ray radiation below 100 keV. It is most widely used for determining the presence of plutonium and ^{241}Am and can be used for estimating radionuclide concentrations in the field.

Operation: The FIDLER consists of a thin beryllium or aluminum window, a thin crystal of NaI or cesium iodide, a quartz light pipe, and a PMT. The probe can have either a 3 in. or 5 in. crystal. The discussion below is applicable to 5 in. crystals. The survey meter requires electronics capable of setting a window about an x-ray or gamma ray energy. This window allows the probe and meter to detect specific energies and, in most cases, provide information about a single element or radionuclide. The window also lowers the background count. Two types of survey meters are generally used with FIDLER probes. One type resembles those used with GM and alpha scintillation probes. They have an analog meter and range switch. The second type is a digital survey meter, which can display the count rate or accumulate counts in a scaler mode for a preset length of time. Both types have adjustable high-voltage and window settings. The advantage of the digital meter is that both background and sample counts can be acquired in scaler mode, yielding a net count above background.

Specificity/Sensitivity: The FIDLER probe is quite sensitive to x-ray and low-energy gamma radiation. Since it can discriminate energies, an energy window can be set that makes it possible to determine the presence of specific radionuclides when the nature of the radioactive material is known. If the identity of a radionuclide is known, the FIDLER can be used to quantitatively determine the concentration. However, interferences can cause erroneous results if other radionuclides are present. The FIDLER can also be used as a survey instrument to detect the presence of x-ray or low-energy gamma photons and to determine the extent of the radioactive material. FIDLER probes are most useful for determining the presence of plutonium and ^{241}Am. These isotopes have a spectrum of x-rays and gamma rays from 13–21 keV that have energies centered around 17 keV, and ^{241}Am has a gamma ray at 59 keV. There is an interference at 13 keV from both americium and uranium x-rays. The FIDLER cannot distinguish which isotope of plutonium is present. Typical sensitivities for plutonium-238 (^{238}Pu) and plutonium-239 (^{239}Pu) at 1 ft above the surface of an area affected by radioactive material are 500–700 and 250–350 cpm/microcuries (μCi)/m^2, respectively. Assuming a soil density of 1.5, uniform concentration within the first 1 mm (0.4 in.) of soil, and a typical background of 400 cpm, the minimum detectable concentration (MDC for ^{238}Pu and ^{239}Pu would be 370 and 740 Bq/kilogram (kg) (10 and 20 pCi/g), or 1,500 and 3,000 Bq/m^2 (900 and 1,800 dpm/100 cm^2) respectively. This MDC is for fresh deposition and will be significantly less as the plutonium migrates into the soil. Because the window is fragile, most operations with a FIDLER probe require a low mass protective cover, such as Styrofoam, cardboard, and other cushioning materials, to prevent damaging the window.

System: Field X-Ray Fluorescence Spectrometer
Field/Laboratory: Field
Radiation Detected: ***Primary:*** X-ray and low-energy gamma radiation ***Secondary:*** None

Applicability to Site Surveys: The system accurately measures relative concentrations of metal atoms in soil or water samples down to the parts per million (ppm) range.

Operation: This system is a rugged type of x-ray fluorescence system that measures the characteristic x-rays of metals as they are released from excited electron structures. The associated electronic and MCA systems are essentially identical to those used with germanium spectrometry systems. The spectra of characteristic x-rays give information for both quantitative and qualitative analysis; however, most frequently, the systems are calibrated only for relative atomic abundance or percent composition.

Specificity/Sensitivity: This is ideal for sites containing metals that have strong x-ray emissions within 5–100 keV. Application for quantification of the transition metals (in the periodic table) is most common because of the x-ray emissions. Operation of this equipment is possible with only a moderate amount of training. The detection capability ranges from a few percent to ppm depending on the particular atoms and their characteristic x-rays. When converted to activity concentration, the MDC for uranium-238 (^{238}U) is approximately 1,850 Bq/kg (50 pCi/g) for typical soil matrices. This method cannot differentiate between different isotopes, so the conversion to ^{238}U assumes that all uranium is ^{238}U, which is a conservative assumption for natural or depleted uranium but not appropriate for enriched uranium.

H.2.4 Large-Area Mobile Detector Arrays

System: Mobile Detector Array Systems
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** None

Applicability to Site Surveys: Surveys over large areas are conducted by attaching an array of detectors to a mobile platform to detect gamma radiation emitted from point or distributed sources.

Operation: A series of detectors, typically a combination of standard off-the-shelf detectors, are arranged in an array aboard a hand cart, trailer, all-terrain vehicle, or motor vehicle and conveyed over an area of interest to detect gamma ray emissions. These detector arrays are generally a series of large (50 mm [2 in.] x 100 mm [4 in.] x 400 mm [16 in.] or 100 mm [4 in.] x 100 mm [4 in.] x 400 mm [16 in.]) NaI, or smaller (50 mm [2 in.] x 50 mm [2 in.]) NaI, or FIDLER detectors. Data are typically collected each second and are georeferenced using Global Positioning System (GPS). The data can be in the form of gross counts, spectra, or both, depending on the detection system and the objectives of the survey. Collected data allow the distinction between natural background radiation levels and levels from the radionuclides of concern. Moreover, if spectral data are collected, identification of radionuclides is possible.

Specificity/Sensitivity: Conversion of mobile count rate information to surface or volumetric soil activity involves a number of parameters, such as detector configuration, scan speed, isotope of interest, specific distribution in the soil, soil density, and moisture. The scan MDC will vary depending on the system's geometry, efficiency, and scan speed. The Data Quality Objectives process should be used to establish survey parameters and ensure sufficient detection capabilities. **Sections 6.3.2** and **6.3.3** contain additional information on establishing scan MDCs and investigation levels for these types of systems.

For a manually controlled system, typical scan speeds are 0.5–1.0 meter (m) per second (s) with a detector standoff distance of 4–12 in. above the surface. The scan MDC for ^{241}Am, with a 50 mm (2 in.) x 50 mm (2 in.) NaI system, scan speed of 1 m/s, and detector height of approximately 100 mm (4 in.), has been documented to be 1,000 Bq/g (28 pCi/g) for large areas of radioactive material.

For a motor-controlled system, typical scan speeds are 1 m/s with a minimum detector standoff distance of approximately 0.3 m (1 ft) above the surface. The scan MDC for ^{241}Am with a dual 100 mm (4 in.) x 100 mm (4 in.) x 400 mm (16 in.) NaI system at the typical speed and detector height has been documented to be 600 Bq/g (17 pCi/g) for large area contamination.

System: Aerial Systems
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** None

Applicability to Site Surveys: Surveys over large areas are conducted through a series of low-level flights using a mounted array of high-efficiency detectors to identify and measure gamma radiation emitted from point or distributed sources.

Operation: A series of detectors, typically a combination of 50 mm (2 in.) x 100 mm (4 in.) x 400 mm (16 in.) NaI detectors, are arranged in an array aboard an airplane or helicopter and flown over an area of interest to detect gamma ray emissions. Data in the form of gamma ray spectra are typically collected each second and georeferenced using GPS. Collected gamma energy spectra allow the system to distinguish between ordinary fluctuations in natural background radiation levels and signatures produced by human-made isotopic sources and to identify unknown radionuclides.

Specificity/Sensitivity: Conversion of airborne count rate information to volumetric soil activity involves a number of parameters, such as type of detector, number of detectors, configuration of detectors, flight altitude and speed, isotope of interest, specific distribution in the soil, soil density, and moisture. To ensure data integrity, georeferencing and monitoring for variations in detector background count rates due to aircraft, radon, and cosmic rays, repeated measurements over a fixed test line, and altitude profiling are typically performed both before and after surveys.

For helicopter-mounted systems, typical flight speeds are between approximately 26–36 m/s (50–70 knots) at altitudes ranging from about 15–150 m (50–500 ft) above ground level (AGL). The minimum detectable activity (MDA) for cesium-137 (^{137}Cs) with an 18-detector system in a helicopter traveling at about 15 m (50 ft) AGL at about 36 m/s (70 knots) is estimated to be approximately 4,400 Bq/m^2 (0.12 µCi/m^2) for uniform distribution on the surface of the ground. At an increased flight altitude of 90 m (300 ft) AGL, this MDA estimate remains valid to within a few percent. At 150 m (500 ft) AGL, the MDA estimate increases to 5,600 Bq/m^2 (0.15 µCi/m^2).

For airplane-mounted systems, typical flight speeds are between about 72–82 m/s (140–160 knots) at altitudes ranging from about 150–460 m (500–1,500 ft) AGL. The ^{137}Cs MDA for a six-detector system in an airplane traveling at about 300 m (1,000 ft) AGL at approximately 82 m/s (160 knots) is estimated to be 19,000 Bq/m^2 (0.5 µCi/m^2).

Unmanned aerial vehicle systems with mounted detectors are under development for other applications and may be available for radiological survey purposes in the future.

H.2.5 Dosimeters

System: Thermoluminescent Dosimeter
Field/Laboratory: Field and laboratory
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** Neutron, beta, x-ray

Applicability to Site Surveys: Thermoluminescent dosimeters (TLDs) can be used to measure such a low dose equivalent that they can identify gamma levels slightly above natural background. TLDs should be placed in areas outside the site but over similar media to determine the average natural background radiation level in the area. Other TLDs should be posted on site to determine the difference from background. Groups of TLDs should be posted for fixed time periods (e.g., duration of project, monthly, quarterly, semiannually) in locations of interest and compared to background radiation TLDs to identify locations of increased onsite doses. The American National Standards Institute (ANSI)/Health Physics Society (HPS) standard ANSI/HPS N13.37, "Environmental Dosimetry" (ANSI/HPS 2019), contains detailed guidance on performance test methods and criteria for system design and implementation of environmental radiation dosimetry systems used to measure external photon radiation.

Operation: A TLD is a crystal that measures radiation dose. TLDs are made up of inorganic scintillation materials that contain small amounts of added impurities. When radiation interacts with the crystal, electrons in the valence band are excited into the conduction band. Many lose their energy and return directly to the valence band, but some are trapped at an elevated energy state by the impurity atoms. This trapped energy can be stored for long periods, but the signal can fade with age, temperature, and light. Heating the TLD releases the excess energy in the form of heat and light. The quantity or intensity of the light given off gives a measure of the radiation dose the TLD received. The TLD is left in the field for fixed time periods and then removed from the field and read in the laboratory on a calibrated TLD reader. The reading is the total dose received by the TLD during the posting period. If the TLDs are processed at an offsite location, the transit dose (e.g., the dose incurred within the TLD from the location to the site and return) must be determined and subtracted from the net dose. The ability to determine this transit dose affects the net detection capability of the measurements.

TLDs come in various shapes (thin rectangles, rods, and powder), sizes (0.08–0.6 cm [0.03–0.25 in.] on a side), and materials (manganese-doped calcium fluoride [CaF_2:Mn]; dysprosium-doped calcium sulfate [$CaSO_4$:Dy]; manganese-doped lithium-6 fluoride [^{6}LiF:Mn]; manganese-doped lithium-7 fluoride [^{7}LiF:Mn]; lithium borate [$LiBO_4$]; magnesium, copper, and phosphorous-doped lithium fluoride [LiF:Mg, Cu, P]; and carbon-doped aluminum oxide [Al_2O_3:C]). The TLD crystals can be held loosely inside a holder, sandwiched between layers of Teflon™, affixed to a substrate, or attached to a heater strip and surrounded by a glass envelope. Most are surrounded by special thin shields to correct for an over-response to low-energy radiation. Many have special radiation filters to allow the same type of TLD to measure various types and energies of radiation.

Specificity/Sensitivity: TLDs are primarily sensitive to gamma radiation, but selected TLD and filter arrangements can be used to measure beta, x-ray, and neutron radiation. They are posted both on site and off site in comparable areas. These readings are compared to determine whether the site can cause personnel to receive more radiation exposure than they would receive from background radiation. The low-end detection capability can be reduced by specially calibrating each TLD and selecting those with high accuracy and good precision. The new Al_2O_3 TLD may be capable of measuring doses as low as 0.1 µSv (0.01 mrem), whereas specially calibrated CaF_2 TLDs posted quarterly can measure dose differences as low as

0.05 mSv/year (y) (5 mrem/y). This contrasts with standard TLDs that are posted monthly and may not measure doses below 1 mSv/y (100 mrem/y). TLDs should be protected from damage as the manufacturer recommends. Some are sensitive to visible light, direct sunlight, fluorescent light, excessive heat, or high humidity.

System: Electronic Dosimeters
Field/Laboratory: Field and laboratory
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** Neutron, beta, x-ray

Applicability to Site Surveys: Similar to TLDs, electronic dosimeters (EDs) can identify gamma levels slightly above natural background. EDs should be placed in areas of similar media (same type of materials found in the area of concern) to determine the average natural background radiation level in that area. Groups of EDs are posted typically for only short durations due to power requirements. Data can be collected incrementally over longer periods, but the collection requires frequent analysis and maintenance of the ED. Application examples include conducting environmental monitoring for site characterization and boundaries, performing shielding studies, and determining exposures to members of the public.

Operation: A silicon diode consists of a junction of two types of semiconductors: P-type and N-type. The operation of a semiconductor depends on having either an excess of electrons or an excess of holes. A semiconductor with an excess of electrons is called an N-type semiconductor, while one with an excess of holes is called a P-type semiconductor. Electrical conduction in each region occurs through the motion of its majority charge carriers (holes or electrons). The electrical contact of the anode (P-type region) and the cathode (N-type region) is obtained by vacuum deposition of a thin metal layer. The difference in charge density between the two regions tends to diffuse charge carriers in the opposite charge region, creating an internal electrical field (or potential barrier) in between, which originates the depleted layer. At ambient temperature, a low current due to thermal agitation—called leakage current—flows through the potential barrier.

When a positive voltage is applied between cathode and anode, electrons are pulled out of the depleted layer, and the current cannot then flow across the junction, except for the small leakage current. The junction is in reverse-biased condition. The thickness of the depletion layer increases with the applied voltage and may reach a few millimeters. When a negative voltage is applied in the same disposition, the potential barrier disappears, and the current flows freely through the junction. These two performing situations correspond to the “diode” effect well known in electronic circuits.

If an ionizing particle passes through the depleted layer while the junction is reverse biased, electron-hole pairs are formed by the usual collision processes. Approximately 10 times more ionizations are formed in semiconductor detectors than in ion chambers for the same energy expenditures. This contributes to the good energy resolution of silicon detectors.

Specificity/Sensitivity: EDs are primarily used for measuring deep-dose gamma radiation. However, some types of EDs can measure low-energy x-rays, beta particles, and neutrons. Gamma-sensitive EDs can measure from 0.1 mrem to 1,000 rem exposure and have an energy response from 60 keV to 6 MeV. Although the primary purpose of an ED is to measure dose, the inclusion of time allows the measurement of dose rates as well, which allows their use as area monitors.

Although EDs are generally resistant to mechanical shock, there are occasions when shock can cause the introduction of false dose. This is called microphonics. Dosimeter components can become more sensitive to microphonics as their board and components age. EDs are also water resistant and are shielded for electromagnetic interference/radiofrequency interference. However, high magnetic fluxes can also cause false dose readings.

Neutron EDs must be calibrated to the energy fields in which they will be used, as they do not have a linear energy response curve; hence, a neutron dosimeter calibrated to the neutron energies from a plutonium-beryllium source may not accurately measure the dose from neutrons emitted from spent nuclear fuel in dry cask storage.

Neutron dosimeter response depends on the energy and fluence of the neutrons being measured. Specific correction factors may be needed for different applications.

System: Optically Stimulated Luminescence Dosimeters
Field/Laboratory: Field and laboratory
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** Neutron, beta, x-ray

Applicability to Site Surveys: Optically stimulated luminescence (OSL) dosimetry provides a nondestructive[2] analysis based on optical—rather than thermal—stimulation to release charge carriers from trapping centers. However, similar to TLDs, OSL devices can identify gamma levels slightly above natural background. OSL dosimeters should be placed in areas over similar media to determine the average natural background radiation level in that area. Groups of OSL dosimeters can be posted for fixed time periods (e.g., duration of project, monthly, quarterly, semiannually) in locations of interest and compared to background radiation to identify locations of increased onsite doses. Application examples include conducting environmental monitoring for site characterization and boundaries, low-level exposure studies for area monitoring, shielding studies, and determining exposure to members of the public.

Operation: OSL is the method of analysis applied to the dosimeter. OSL dosimeters are made of inorganic scintillation materials that contain small amounts of added impurities: carbon-doped aluminum oxide (Al_2O_3:C) crystals. OSL dosimeters are sensitive to beta and photon radiation. OSL devices sensitive to neutrons (OSLNs) are made up of Al_2O_3:C coated with lithium carbonate enriched with lithium-6 ($^6Li_2CO_3$, 95 percent enriched) and are sensitive to beta, photon, and neutron radiation. The amount of radiation exposure is measured by stimulating the Al_2O_3:C material with green light from either a laser or light-emitting diode source. The resulting blue light emitted after stimulation indicates the level of radiation exposure. This can be done repeatedly to verify a radiation exposure or to accumulate a total dose over time. OSL has no light-induced artifacts or light-induced changes and provides a comparatively permanent record.

Two types of instruments can read OSL dosimeters: automated laboratory-grade instruments, and portable reader “plug-in and operate” instruments for field use with manual reading of OSL dosimeters. Both readers use the OSL technique to analyze the dosimeters through a computer interface. The field reader allows measurement on demand, and the OSL dosimeters can be sent to a laboratory for additional measurement as needed.

The dosimeter consists of a case that contains metal and plastic filters and a plastic slide containing detector elements. The detector element is a layer of Al_2O_3:C sandwiched between two layers of polyester, for a total thickness of 0.3 mm (0.12 in.). The environmental dosimeter contains the open window, plastic, and copper filters only. The OSL dosimeter is of rectangular design, 5 cm x 2.4 cm x 0.6 cm (1.97 in. x 0.94 in. x 0.24 in.) thick, and constructed of polystyrene plastic. Two flexible black gaskets are applied to the case to prevent light entry under extreme outdoor conditions. The waterproof holder is of rectangular design, 6.3 cm x 4.5 cm x 0.6 cm (2.48 in. x 1.77 in. x 0.24 in.) thick, constructed of polyvinyl chloride plastic, and radiofrequency sealed. The OSL dosimeter is left in the field for fixed time periods and then removed from the field and read in the laboratory on a calibrated reader. The reading is the total dose received by the OSL dosimeter during the posting period. If the OSL dosimeter is processed at an offsite location, the transit dose (e.g., dose incurred within the OSL from the

[2] Generically, a nondestructive analytical technique is an analytical technique that is not causing the destruction of material being investigated or treated. However, in certain cases, a nondestructive analytical technique may refer to the analysis of probe samples that do not need to be dissolved since probes at the micro scale (1–300 micrometers) are analyzed. In this case, only such small probes are destroyed, whereas the rest of the sample can be preserved for further analysis. In other words, such techniques are destructive at the micro scale but do not destroy the bulk of the sample.

location to the site and return) must be determined and subtracted from the net dose. The ability to determine this transit dose affects the net detection capability of the measurements.

Specificity/Sensitivity: OSL dosimeters are primarily sensitive to gamma radiation, but selected filter arrangements can be used to measure beta and x-ray radiation. The dosimeters are posted both on site and off site in comparable areas. These readings are compared to determine whether the site can cause personnel to receive more radiation exposure than they would receive from background radiation. The nominal lower limit of detection (LLD) for photon exposures as a function of exposure days is about 0.04 mSv (4 mrem) for 1–30 days exposure, about 0.05 mSv (5 mrem) for 30–60 days exposure, and about 0.1 mSv (10 mrem) for more than 200 days exposure. OSL dosimeters may be capable of measuring nominal doses as low as 1 μSv (0.1 mrem) reporting to tenths of an mrem ambient dose equivalent. Photons (x-rays and gamma rays) with energies above 15 keV can be measured in the range of 1 μSv to 10 sieverts (Sv) (0.1 mrem to 1,000 rem). Beta particles with average energies greater than approximately 500 keV can be measured in the range 200 μSv to 10 Sv (20 mrem to 1,000 rem). OSL and OSLN dosimeters measure doses with good linearity over more than 4 orders of magnitude from 0.01 mSv (1 mrem) to 10 Sv (1,000 rem), ^{137}Cs equivalent, and tested to 12,500 mGy (1,250 rad) to verify that saturation does not occur. Expected bias is within 1 percent from 0–100 R, 5 percent from 100–500 R, and 10 percent from 500–1,000 R and response within ±2 percent from 0–500 R and ±4 percent at 1,000 R.

H.2.6 Radon Detectors

System: Activated Charcoal Adsorption
Field/Laboratory: Field and laboratory
Radiation Detected: ***Primary:*** Radon gas ***Secondary:*** None

Applicability to Site Surveys: Activated charcoal adsorption is a passive, low-cost screening method for measuring indoor air radon concentration. The charcoal adsorption method is not designed for outdoor measurements of ambient radon concentrations, but it can be used for flux measurements. For structures affected by residual radioactive material, charcoal is a good short-term indicator of the presence of radon. Vendors provide measurement services, which include the detector and subsequent readout. Radon flux can also be measured by adsorption onto charcoal using a variety of methods, such as a charcoal canister.

Operation: For this method, an airtight container with activated charcoal is opened in the area to be sampled, and radon in the air adsorbs onto the charcoal by molecular diffusion. The detector, depending on its design, is deployed for 2–7 days. At the end of the sampling period, the container is sealed and sent to a laboratory for analysis. Proper deployment and analysis will yield accurate results.

Two analysis methods are commonly used in activated charcoal adsorption. The first method calculates the radon concentration based on the gamma decay from the radon progeny analyzed on a gamma scintillation or semiconductor detection system. The second method is liquid scintillation, which employs a small vial containing activated charcoal for sampling. After exposure, scintillation fluid is added to the vial, and the radon concentration is determined by the alpha and beta decay of the radon and progeny when counted in a liquid scintillation spectrometer.

To measure the radon flux, the activated charcoal is removed after 24 hours of exposure and transferred to plastic containers. The amount of radon adsorbed on the activated charcoal is determined by gamma spectroscopy. Because the area of the surface is well defined and the deployment period is known, the radon flux (in units of Bq/m^2-s or pCi/m^2-s) can be calculated.

Specificity/Sensitivity: Charcoal canisters are designed to measure radon concentrations in indoor air. Some charcoal absorbers are sensitive to drafts, airflow extremes, temperature, and humidity. However, the use of a diffusion barrier over the charcoal reduces these effects. The MDC for this method ranges from 0.007–0.04 millibecquerel (mBq)/m^3 (Bq/liter [L]) (0.2–1.0 pCi/L).

System: Alpha Track Detector
Field/Laboratory: Field and laboratory
Radiation Detected: ***Primary:*** Alpha particles (radon gas) ***Secondary:*** Thoron (^{220}Rn)

Applicability to Site Surveys: An alpha track detector is a passive, low-cost, long-term method used for measuring radon. Alpha track detectors can be used for site assessments both indoors and outdoors (with adequate protection from the elements).

Operation: Alpha track detectors employ a small piece of special plastic or film inside a small container. Air being tested diffuses through a filtering mechanism into the container. When alpha particles from the decay of radon and its progeny strike the detector, they cause damage tracks. At the end of exposure, the container is sealed and returned to the laboratory for analysis.

The plastic or film detector is chemically treated to amplify the damage tracks and then the number of tracks over a predetermined area is counted using a microscope, optical reader, or spark counter. The radon concentration is determined by the number of tracks per unit area. Detectors are usually exposed for 3–12 months, although shorter time frames may be used when measuring high radon concentrations. If a diffusive barrier is added to the detector in a supplemental manner, the barrier is capable of significantly reducing the contribution of thoron (radon-220 [^{220}Rn]) and its progeny to the total alpha track count. Therefore, the ^{220}Rn air concentration can be estimated by subtracting the alpha track count taken without ^{220}Rn contribution from the total track count and converting the result to thoron air concentration.

Specificity/Sensitivity: Alpha track detectors are primarily used for indoor air measurements, but specially designed detectors are available for outdoor measurements. Alpha track results are usually expressed as the integrated radon concentration over the exposure period (Bq/L^{-1}-day$[d]^{-1}$). The detection capability is a function of detector design and exposure duration and also a function of the size of the area being read by the laboratory. It is on the order of 0.04 mBq/m^3-d (0.04 Bq/L-d; 1 pCi/L-d).

System: Continuous/Integrating Radon Monitor
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Alpha particles (radon gas) ***Secondary:*** None

Applicability to Site Surveys: Radon monitors are devices that measure and record real-time measurements of radon gas or variations in radon concentration in a continuous (typically at least once every 10 minutes) or integrating (longer than 1 hour) mode. Because continuous monitors display real-time radon measurements, they are useful for short-term site investigation.

Operation: Continuous radon monitors are precision devices that track and record real-time measurements and variations in radon gas concentration on an hourly basis. Air either diffuses or is pumped into a counting chamber. The counting chamber is typically a scintillation cell, ionization chamber, or a sample cell equipped with a solid-state alpha detector. Using a calibration factor, the counts are processed electronically, and radon concentrations for predetermined intervals are stored in memory or directly transmitted to a printer.

The operation of monitors equipped with solid-state detectors is based on an electrostatic collection of alpha emitters with spectral analysis. The electric field within the sample cell drives the positively charged ion to the detector, where it sticks. The detector converts alpha radiation directly to an electrical signal proportional in strength to the energy of the alpha particle.

Most continuous monitors are used for a relatively short measurement period, usually several minutes to several days. Consensus radon standards of practice as of 2017 require a minimum measurement of at least 48 hours in buildings. State standards may be different. These devices do require some operator skill and often have a ramp-up period to equilibrate with the surrounding atmosphere. This ramp-up time can range from 1–4 hours, depending on the size of the counting chamber and rate of air movement into the chamber. Some instruments in the higher cost range measure both radon and thoron concentrations. “Sniff” mode with very short sampling may be used to locate radon entry points in buildings. Some instruments require desiccants or external air-drying devices to dry incoming air.

Specificity/Sensitivity: Most continuous monitors are designed for both indoor and outdoor radon measurements. The limiting factor for outdoor use is the need for electrical power. If external power is unavailable, the available operating time depends on the battery life of the monitor. The MDC for these detectors ranges from 0.004–0.2 Bq/L (0.1–5.0 pCi/L), depending on sample time.

System: Electret Ion Chamber
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Alpha, beta, or gamma (radon gas) ***Secondary:*** None

Applicability to Site Surveys: Electrets are primarily used to measure radon concentration in indoor environments. For structures affected by residual radioactive material, the electret ion chamber is a good indicator of short-term and long-term radon concentrations. Electrets may be used to measure radon flux from the ground or materials. They can also be configured as a passive integrating detector for measurements of alpha- or low-energy beta-emitting radionuclides on surfaces and in soils or gamma radiation dose in the environment.

Operation: The system consists of a charged electret (e.g., Teflon™ disk), small ionization chamber, and electret voltage reader/data logger. For all measurements, an electret is placed within the chamber, establishing a static electric field and forming a passive ionization chamber. For radon measurements, radon diffuses through a filter into the ion chamber. The decay energy of radon and its progeny ionizes air in the chamber. The air ionization products are collected on the electret and reduce the charge on the electret and electric field strength of the electret. The strength of the electric field is measured with the voltage reader before and after deployment. The rate of change of the electric field strength, with applied calibration, background, gamma rate, and elevation compensation factors, is proportional to the air radon concentration. Because the detectors are sensitive to gamma radiation, a gamma correction will be needed when measuring radon. This can be done with two electret ion chambers or a gamma measurement. Variations in electret design enable the detector to make short- or long-term measurements. Short-term detectors are deployed for 2–7 days, whereas long-term detectors may be deployed from 1–12 months.

For alpha or beta measurements, the chamber is opened and deployed directly on the surface or soil to be measured so that the particles can enter the chamber. A thin Mylar™ window may be used to protect the electret from dust. Corrections must be made for background gamma radiation and radon response. This is accomplished by deploying additional gamma- or radon-sensitive detectors in parallel with the alpha or beta detector.

For gamma measurements, the chamber is left closed, and the gamma rays incident on the chamber penetrate the 2 mm (0.08 in.) thick plastic detector walls. These photons ionize the air molecules, and the resulting ions are attracted to the charged electret, reducing the electret's charge. For low-level gamma measurements, the electret is sealed inside a Mylar™ bag during deployment to minimize radon interference.

The chambers are sensitive to temperature as well. The temperature issue is sometimes a function of the temperature changes of the voltage reading device, and it does take time for the device to acclimate. It can be used in the field, but taking the device in and out of a vehicle for readings could be problematic.

Electrets are simple and relatively inexpensive, and they can be used several times before discharging or requiring recharge by a vendor, except in areas of extreme radon concentrations. It is recommended to take initial and final voltage readings in the same or similar environmental conditions, considering humidity and temperature. Because of their small size (3.8 cm [1.5 in.] tall x 7.6 cm [3 in.] in diameter), electrets may be deployed in hard-to-access locations.

Specificity/Sensitivity: Electrets are designed to measure radon primarily in indoor environments, but they can also be used outdoors for flux measurements. The lower limit of detection depends on the exposure time and the volume of chamber used. The MDC for radon

measurements ranges from 0.007–0.02 mBq/m^3 (Bq/L) (0.2–0.5 pCi/L) for a nominal 3-month measurement.

For other measurements, high concentrations of surface alpha or beta activity or high gamma radiation levels may be measured with deployment times of a few minutes. Much lower levels can be measured by extending the deployment time to 24 hours or longer.

For alpha radiation, the lower limit of detection is 83 Bq/m^2 (50 dpm/100 cm^2) at 1 hour, 25 Bq/m^2 (15 dpm/100 cm^2) at 8 hours, and 13 Bq/m^2 (8 dpm/100 cm^2) at 24 hours.

For beta radiation, the lower limit of detection for ^{3}H is 10,000 Bq/m^2 (6,000 dpm/cm^2) at 1 hour and 500 Bq/m^2 (300 dpm/cm^2) at 24 hours; for technetium-99 (^{99}Tc), the lower limit of detection is 830 Bq/m^2 (500 dpm/cm^2) at 1 hour and 33 Bq/m^2 (20 dpm/cm^2) at 24 hours.

For gamma radiation, the response of the detector is nearly independent of energy from 15–1,200 keV, and fading corrections are not required. To quantify ambient gamma radiation fields of 10 µR/h, a 1,000 milliliter (mL) chamber may be deployed for 2 days or a 50 mL chamber deployed for 30 days. The smallest chamber is particularly useful for long-term monitoring and reporting of monthly or quarterly measurements.

Care must be taken to measure the background gamma radiation at the site during the exposure period. Extreme temperatures and humidity encountered outdoors may affect electret voltage.

System: Large-Area Activated Charcoal Collector
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Alpha particles (radon gas flux) ***Secondary:*** None

Applicability to Site Surveys: This method is used to make radon flux measurements (the surface emanation rate of radon gas) and involves the adsorption of radon on activated carbon in a large-area collector.

Operation: The collector consists of a polyvinyl chloride end cap approximately 250 mm (10 in.) in diameter, spacer pads, a charcoal distribution grid, a retainer pad with screen, and a steel retainer spring. Between 170 and 200 g of activated charcoal are spread in the distribution grid and held in place by the retainer pad and spring.

The collector is deployed by firmly twisting the end cap into the surface of the material to be measured. After 24 hours of exposure, the activated charcoal is removed and transferred to plastic containers. The amount of radon adsorbed on the activated charcoal is determined by gamma spectroscopy. These data are used to calculate the radon flux in units of Bq m^{-2} s^{-1}.

Specificity/Sensitivity: These collectors give an accurate short-term assessment of the radon gas surface emanation rate from a material. The MDC of this method is 0.007 Bq m^{-2} s^{-1} (0.2 pCi m^{-2} s^{-1}).

Exposures for longer than 24 hours are not recommended because of atmospheric and surface moisture and temperature extremes, which may saturate the charcoal or affect charcoal efficiency.

H.2.7 Specialized Instrumentation

System: Laser Ablation-Inductively Coupled Plasma-Atomic Emission Spectrometry and Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry
Field/Laboratory: Field
Radiation Detected: None (direct detection of isotopes based on mass-to-charge ratio)

Applicability to Site Surveys: Laser ablation-inductively coupled plasma-atomic emission spectrometry (LA-ICP-AES) and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) are techniques used to screen and characterize very small samples of soils and concrete in situ (e.g., without dissolution of the sample) to determine the concentration of elements or radioisotopes in the material. Laser ablation is particularly suited to measuring the surface concentration of uranium and thorium. The concentrations at various depths can be determined as the laser ablates surface levels and exposes underlying surfaces to the laser beam. It has the advantage of providing real-time response, reducing sampling and analysis time, and keeping personnel clear of the materials being sampled.

Operation: LA-ICP-MS uses a laser to produce pulses of high-energy ultraviolet light that are focused onto the sample surface using a microscope-like lens. The laser can be focused to an area of a few micrometers in diameter. The sample is held in an enclosed cell mounted on a movable stage, so the sampling point can be moved beneath the laser beam. Each laser pulse creates a plasma discharge that ablates the sample surface, removing material for analysis. The ablated material is carried in a gas flow (usually helium) from the ablation cell through a flexible tube to the inductively coupled plasma-mass spectrometry (ICP-MS) portion of the instrument. In the argon plasma (the ICP), the ablated sample material is decomposed, atomized, and ionized before being passed into an atomic emission spectrometer (AES) or mass spectrometer for analysis.

In brief, the main components of the system include a sampling system, fiber optics cables, a spectrometer, a potable water supply, cryogenic and high-pressure gas supplies, a robotics arm, control computers, an ICP torch, and a video monitor. **Figure H-1** at the end of this section shows a schematic of the ICP-MS system's main components.

With the incorporation of a portable laser ablation/sample cell probe, the system can be used in the field, though still requiring an attached laboratory inductively coupled plasma-atomic emission spectrometry/mass spectrometry (ICP-AES/MS) analysis. For example, the Mobile Demonstration Laboratory for Environmental Screening Technologies (MDLEST) represented a completely self-contained mobile laboratory containing the instrumentation to immediately analyze the samples generated by the laser ablation. Portable sampling probes were developed for use in screening/characterizing surface soils, concrete floors or pads, and subsurface soils. A sampling probe could be connected using a 20 m umbilical to the ICP-AES/MS instrumentation of the MDLEST. The analysis instrumentation (i.e., ICP-AES/MS) in the MDLEST did not depend on radioactive decay for detection but looked directly at the atomic makeup of the element(s) of interest. The spectrometer could be set up using either hardware, software, or both to simultaneously detect all elements of interest in each sample using the MDLEST system. The MDLEST system could be set up on site to monitor soil treatment processes, enabling the remediation manager to monitor in real time the treatment processes removing the residual radioactive material and to ensure that satisfactory agreement with both regulatory agency and quality control/quality assurance requirements was attained. Anderson and Braymen (1995) provide a detailed description and application of MDLEST. YouTube®

videos related to MDLEST can be found at https://www.youtube.com/@mdlest-usdoe-ameslab1869/featured.

Many metal elements, including the longer half-life radioactive elements, can be detected and quantified using LA-ICP-MS. For example, determination of ^{99}Tc in environmental samples has been reported in the literature (Morita et al. 1991).

Specificity/Sensitivity: LA-ICP-AES and LA-ICP-MS measure the surface or depth concentration of atomic species and are particularly suited to uranium and thorium analysis. They are highly effective with skilled operators. Some advantages are the lack of contact with the soil, real-time results, and no samples of which to dispose. The sample results are quickly available for field remediation decisions, with the LA-ICP-AES taking about 10 minutes and the LA-ICP-MS taking about 30 minutes. The following detection limits have been used for the two spectrometers:

- The LA-ICP-AES can detect concentrations at the ppm level for some 70 elements and reportedly detects uranium and thorium concentrations at 1 ppm, or 12 Bq/kg (0.33 pCi/g) for ^{238}U and 0.41 Bq/kg (0.11 pCi/g) for thorium-232 (^{232}Th). However, the technique is sensitive only to elements; it cannot discriminate between the different isotopes of uranium and thorium. This prevents it from being used for assessing elements with lower atomic numbers that have stable isotopes or from determining relative abundances of isotopes of any element. This may significantly limit its use at some sites.

- The LA-ICP-MS can detect concentrations at the sub-part per billion (ppb) level and is capable of quantifying the uranium and thorium isotopes. This system has been used to search for ^{230}Th and radium-226 (^{226}Ra) and is reportedly useful in reaching 0.8 ppm or 0.6 Bq/g (15 pCi/g) for ^{230}Th content for remediated soil. It appears to measure uranium and thorium concentrations in soil more sensitively than the LA-ICP-AES system. Also, it has been used to determine other isotopes such as ^{99}Tc (refer to Morita et al. 1991), as it has been shown that the LA-ICP-MS can be used at a detection limit of 1.1 mBq/mL (1.73 picograms [pg]/mL), with agreement with a liquid scintillation counting system within a 3 percent relative deviation.

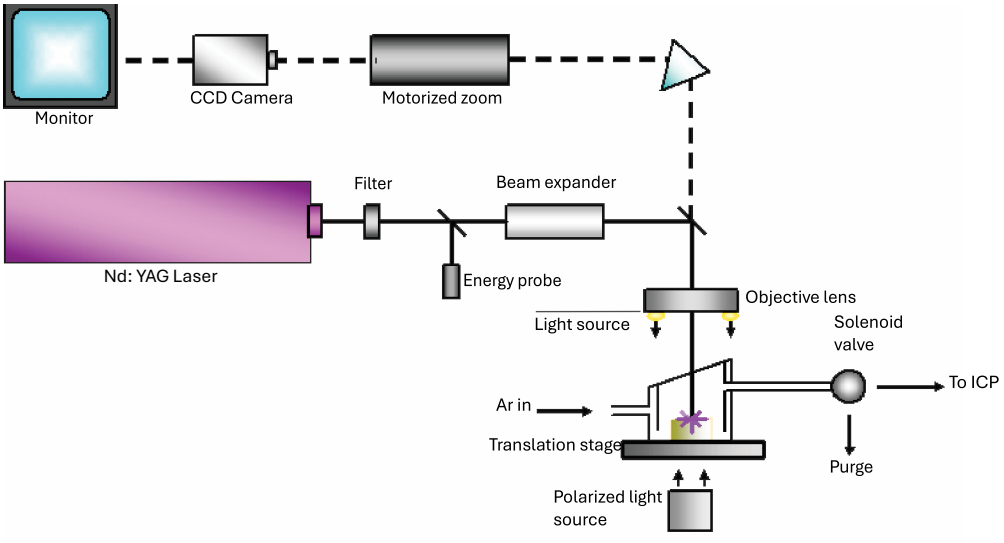

Figure H-1 A Schematic of Nd: YAG LA System (5th harmonic—213 nm) for ICP-MS (Neufeld 2005)

H.3 Laboratory Instruments

H.3.1 Alpha Particle Analysis

System: Alpha Spectroscopy with Multichannel Analyzer
Field/Laboratory: Laboratory
Radiation Detected: ***Primary:*** Alpha ***Secondary:*** None

Applicability to Site: This is a very powerful tool for accurately identifying and quantifying the activity of multiple alpha-emitting radionuclides in a sample of soil, water, air filters, or other media. Methods exist for the analyses of most alpha-emitting radionuclides, including uranium, thorium, plutonium, polonium, and americium. Samples must first be prepared in a chemistry laboratory to isolate the radionuclides of interest from the environmental matrix.

Operation: This system consists of an alpha detector housed in a light-tight vacuum chamber, a bias voltage supply, amplifier, analog-to-digital converter, MCA, and computer. The bias is typically 25–100 V. The vacuum is typically less than 10 micrometers of mercury (at 0 degrees Celsius). The probe face area is 10–20 cm^2. The detector is a silicon diode that is reverse biased. Alpha particles that strike the diode create electron-hole pairs; the number of pairs is directly related to the energy of each alpha. These pairs cause the diode to break down and a current pulse to flow. The charge is collected by a preamplifier and converted to a voltage pulse proportional to the alpha energy. It is amplified and shaped by an amplifier. The MCA stores the resultant pulses and displays a histogram of the number of counts versus alpha energy. Because most alphas will lose all of their energy to the diode, peaks are seen on the MCA display that can be identified by specific alpha energies. Two system calibrations are necessary. A source with at least two known alpha energies is counted to correlate the voltage pulses with alpha energy. A standard source of known activity is analyzed to determine the system efficiency for detecting alphas. Because the sample and detector are in a vacuum, most commonly encountered alpha energies will be detected with approximately the same efficiency, provided there is no self-absorption in the sample. Samples are prepared in a chemistry

laboratory, where they are placed in solution and the element of interest (uranium, plutonium, etc.) is separated. A tracer of known activity is added before separation to determine the overall recovery of the sample from the chemical procedures. The sample is converted to a particulate having very little mass and collected on a special filter, or it is collected from solution by electroplating onto a metal disk. It is then placed in the vacuum chamber at a fixed distance from the diode and analyzed. For environmental levels, samples are typically analyzed for 1,000 minutes or more.

Specificity/Sensitivity: The system can accurately identify and quantify the various alpha-emitting radioactive isotopes of each elemental species, provided each has a different alpha energy that the system can resolve. For soils, a radionuclide can be measured below 0.004 Bq/g (0.1 pCi/g). The system is appropriate for all alphas except those from gaseous radionuclides.

System: Low-Resolution Alpha Spectroscopy
Field/Laboratory: Laboratory (soil samples)
Radiation Detected: ***Primary:*** Alpha ***Secondary:*** None

Applicability to Site Surveys: Low-resolution alpha spectroscopy is a method for measuring alpha activity in soils with a minimum of sample preparation. Some isotopic information can be obtained.

Operation: The system consists of a silicon detector with a diameter of 50 mm (2 in.), a small vacuum chamber, a roughing pump, an MCA, a laptop or benchtop computer, and analysis software. Soil samples are dried, milled to improve homogeneity, distributed into 50 mm (2 in.) planchets, loaded into the vacuum chamber, and counted. The accumulated alpha spectrum is displayed in real time. When sufficient counts have been accumulated, the spectrum is transferred to a data file, and the operator inputs the known or suspected radionuclides of concern. The analysis software then fits the alpha spectrum with a set of trapezoidal peaks, one for each isotope, and outputs an estimate of the specific activity of each isotope.

Specificity/Sensitivity: This method fills the gap between gross alpha analysis and radiochemical separation/high-resolution alpha spectroscopy. Unlike gross alpha analysis, it does provide some isotopic information. Because this is a low-resolution technique, isotopes with energies closer than approximately 0.2 MeV cannot be separated. For example, ^{238}U (4.20 MeV) can be readily distinguished from uranium-234 (^{234}U) (4.78 MeV), but ^{230}Th (4.69 MeV) cannot be distinguished from ^{234}U.

Because no chemical separation of isotopes is involved, only modest MDCs can be achieved. Detection limits are determined by the background alpha activity in the region of interest of the radionuclide of concern and by the counting time. Typical MDCs are 1,500 Bq/kg (40 pCi/g) at 15 minutes counting time, 260 Bq/kg (7 pCi/g) at 8 hours, and 185 Bq/kg (5 pCi/g) at 24 hours. The method does not generate any new waste streams and does not require a sophisticated laboratory or highly trained personnel.

H.3.2 Alpha/Beta Particle Analysis

System: Gas-Flow Proportional Counter
Field/Laboratory: Laboratory
Radiation Detected: ***Primary:*** Alpha, beta ***Secondary:*** Gamma

Applicability to Site Surveys: This system can determine the gross alpha or gross beta activity of water, soil, air filters, or swipes. Results can indicate whether nuclide-specific analysis is needed.

Operation: The system consists of a gas-flow detector, supporting electronics, and an optional guard detector for reducing background count rate. A thin window (<0.1 mg/cm^2 window, probe face area 10–20 cm^2) can be placed between the gas-flow detector and sample to protect the detector from contamination, or the sample can be placed directly into the detector. Systems with guard detectors operate sample and guard detectors in anticoincidence mode to reduce the background and MDC. The detector high voltage and discriminator are set to count alpha radiation, beta radiation, or both simultaneously. The alpha and beta operating voltages are determined for each system by placing an alpha source, such as ^{230}Th or ^{241}Am, in the detector and increasing the high voltage incrementally until the count rate becomes constant, then repeating with a beta source, such as ^{90}Sr. The alpha plateau, or region of constant count rate, should have a slope less than 2%/100 V and be more than 800 V long. The beta plateau should have a slope of less than 2.5%/100 V and be more than 200 V long. Operation on the beta plateau will also allow detection of some gamma radiation and bremsstrahlung (a type of x-ray), but the efficiency is very low. Crosstalk between the alpha-to-beta channels is typically approximately 10 percent, whereas beta-to-alpha channels should be less than 1 percent. The activity in soil samples is chemically extracted, separated if necessary, deposited in a thin layer in a planchet to minimize self-absorption, and heated to dryness. Liquids are deposited and dried, whereas air filters and swipes are placed directly in the planchet. After each sample is placed under the detector, P-10 counting gas constantly flows through the detector. Systems with automatic sample changers can analyze tens to hundreds of planchet samples in a single run.

Specificity/Sensitivity: Natural radionuclides present in soil samples can interfere with the detection of other radionuclides. Unless the nature of the residual radioactive material and any naturally occurring radionuclides is well known, this system is better used for screening samples. Although it is possible to use a proportional counter to roughly determine the energies of alpha and beta radiation, the normal mode of operation is to detect all alpha events or all alpha and beta events. Some systems use a discriminator to separate alpha and beta events, allowing simultaneous determination of both the alpha and beta activity in a sample. These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radionuclides. The alpha channel background is very low, less than 0.2 cpm (<0.04 cpm guarded), depending on detector size. Typical (4π) efficiencies for very thin alpha sources are 35–45 percent (window) or 40–50 percent (windowless). Total efficiency depends on window thickness, particle energy, source-detector geometry, backscatter from the sample and holder, and detector size. The beta channel background ranges from 2–15 cpm (<0.5 cpm guarded). The total efficiency for a thin ^{90}Sr/^{90}Y source is more than 50 percent (window) to more than 60 percent (windowless) but can reduce to less than 5 percent for a thick source. MDAs for guarded gas-flow proportional counters are somewhat lower than for internal proportional counters because of the lower backgrounds.

System: Liquid Scintillation Spectrometer
Field/Laboratory: Laboratory (primary), field (secondary)
Radiation Detected: ***Primary:*** Alpha, beta ***Secondary:*** Gamma

Applicability to Site Surveys: Liquid scintillation can be a very effective tool for measuring the concentration of radionuclides in soil, water, air filters, and smears. Liquid scintillation has historically been applied more to beta emitters, particularly the low-energy beta emitters ^{3}H and carbon-14 (^{14}C), but it can also apply to other radionuclides. More recently, it has been used for measuring radon in air and water. Initial scoping surveys may be done (particularly for loose radioactive material on surfaces) with surface swipes or air particulate filters. They may be counted directly in liquid scintillation counters (LSCs) with no paper dissolution or other sample preparation.

Operation: The liquid scintillation process involves detection of light pulses (usually in the near-visible range) by PMTs (or conceptually similar devices). The detected light pulses originate from the restructuring of previously excited molecular electron structures. The molecular species that first absorb and then readmit the visible light are called liquid scintillators, and the solutions in which they reside are called liquid scintillation cocktails. For gross counting, samples may be placed directly into an LSC vial of cocktail and counted with no preparation. Inaccuracies result when the sample itself absorbs the radiation before it can reach the LSC cocktail or when the sample absorbs the light produced by the cocktail. For accurate results, these interferences are minimized. Interferences in liquid scintillation counting due to the inability of the solution to deliver the full energy pulse to the photomultiplier detector, for a variety of reasons, are called “pulse quenching.” Raw samples that cloud or color the LSC cocktail so the resulting scintillations are absorbed will quench the sample and result in underestimates of the activity. Such samples are first processed by ashing, radiochemical or solvent extraction, or pulverizing to place the sample in intimate contact with the LSC cocktail. Actions like bleaching the sample may also be necessary to make the cocktail solution transparent to the wavelength of light it emits. The analyst has several reliable computational or experimental procedures to account for quenching. One is by exposing the sample and pure cocktail to an external radioactive standard and measuring the difference in response.

Specificity/Sensitivity: The method is extremely flexible and accurate when used with proper calibration and compensation for quenching effects. Energy spectra are 10–100 times broader than gamma spectrum photopeaks, so quantitative determination of complex multienergy beta spectra is impossible. Sample preparation can range from none to complex chemical reactions. In some cases, liquid scintillation offers many unique advantages, such as no sample preparation before counting, which is in contrast to conventional sample preparation for gas proportional counting. Recent advances in electronic stability and energy pulse shape discrimination have greatly expanded uses. Liquid scintillation counters are ideal instruments for moderate- to high-energy beta and alpha emitters, where the use of pulse shape discrimination has allowed dramatic increases in sensitivity by electronic discrimination against beta and gamma emitters. Additionally, very high energy beta emitters (above 1.5 MeV) may be counted using liquid scintillation equipment by use of the Cerenkov light pulse emitted as high-energy charged particles move through water or similar substances.

H.3.3 Gamma Ray Analysis

System: Sodium Iodide Detector with Multichannel Analyzer
Field/Laboratory: Laboratory
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** None

Applicability to Site Surveys: This system accurately measures the activity of gamma-emitting radionuclides in a variety of materials, such as soil, water, and air filters, with little preparation. NaI is inherently more efficient for detecting gamma rays but has lower resolution than germanium. The lower resolution can present difficulties if multiple radionuclides and complicated spectra are involved.

Operation: This system consists of an NaI detector, a high-voltage power supply, an amplifier, an analog-to-digital converter, and an MCA. The detector is an NaI crystal connected to a PMT. Crystal shapes can vary extensively, and typical detector high voltage ranges from 900–1,000 V. A gamma ray interacting with an NaI crystal produces light, which is passed to the PMT. This light ejects electrons, which the PMT multiplies into a pulse that is proportional to the energy the gamma ray imparted to the crystal. The MCA assesses the pulse size and places a count in the corresponding channel. The count rate and energy spectrum are displayed with the full energy photopeaks, providing more useful information than the general smear of Compton scattering events shown in between. The system is energy calibrated using isotopes that emit at least two gamma ray energies, so the data channels are given an energy equivalence and displayed as photopeak intensity versus energy. A nonlinear energy response and lower resolution make isotopic identification less precise than with a germanium detector. Efficiency calibration is performed using known concentrations of single or mixed isotopes. The single isotope method develops a count rate-to-activity factor. The mixed isotope method produces a gamma ray energy versus counting efficiency curve that shows that NaI is most sensitive around 100–120 keV and trails off to either side. Counting efficiency is a function of sample-to-detector distance, so each geometry must have a separate efficiency calibration curve. The center of each peak indicates the gamma ray energy that produced it, and the combination of peaks identifies each isotope. Although the area under a peak relates to that isotope's activity in the sample, integrating a band of channels often provides better detection capability. Samples are placed in containers and tare weighed. Plastic petri dishes sit atop the detector and are useful for small volumes or low energies, whereas Marinelli beakers fit around the detector and provide exceptional counting efficiency for volume samples.

Specificity/Sensitivity: This system analyzes gamma-emitting isotopes with minimum preparation and better efficiency, but lower resolution compared to most germanium detectors. Germanium detectors do reach efficiencies of 150 percent compared with a 7.5 cm (3 in.) x 7.5 cm (3 in.) NaI detector, but the increase in efficiency can be prohibitively expensive. The instrument response is energy dependent, and the resolution is in the tens of keV range, so care should be taken when identifying or quantifying multiple isotopes. Computer software can help interpret complicated spectra. The NaI detector is fragile and should be protected from shock and sudden temperature changes.

System: Germanium Detector with Multichannel Analyzer
Field/Laboratory: Laboratory
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** None

Applicability to Site: This system accurately measures the activity of gamma-emitting radionuclides in a variety of materials like soil, water, and air filters with little preparation. Germanium is especially powerful in dealing with multiple radionuclides and complicated spectra.

Operation: This system consists of a germanium detector connected to a dewar of liquid nitrogen, a high-voltage power supply, a spectroscopy-grade amplifier, an analog-to-digital converter, and an MCA. P-type germanium detectors typically operate from +2,000 to +5,000 V; N-type germanium detectors operate from -2,000 to -5,000 V. When a gamma ray interacts with a germanium crystal, it produces electron-hole pairs. An electric field is applied, which causes the electrons to move in the conduction band and the holes to pass the charge from atom to neighboring atom. The charge is collected rapidly and is proportional to the deposited energy. The count rate/energy spectrum is displayed on the MCA screen with the full-energy photopeaks providing more useful information than the general smear of Compton scattering events shown in between. The system is energy calibrated using isotopes that emit at least two known gamma ray energies, so the MCA data channels are given an energy equivalence. The MCA's display then becomes a display of intensity versus energy. Efficiency calibration is performed using known concentrations of mixed isotopes. A curve of gamma ray energy versus counting efficiency is generated, and it shows that P-type germanium is most sensitive at 120 keV and trails off to either side. Because the counting efficiency depends on the distance from the sample to the detector, each geometry must be given a separate efficiency calibration curve. Computer programs now exist that perform mathematical efficiency calibrations of germanium detectors, without any application of radioactive sources by the laboratory user. This allows for quick and accurate calibrations of many geometries that (1) are difficult to perform, (2) require reference sources, or (3) require knowledge of radiochemistry. From that point, the center of each gaussian-shaped peak indicates the gamma ray energy that produced it, the combination of peaks identifies each isotope, and the area under selected peaks is a measure of the amount of that isotope in the sample. Samples are placed in containers and tare weighed. Plastic petri dishes sit atop the detector and are useful for small volumes or low energies, whereas Marinelli beakers fit around the detector and provide exceptional counting efficiency for volume samples.

Specificity/Sensitivity: The system accurately identifies and quantifies the concentrations of multiple gamma-emitting radionuclides in such samples as soil, water, and air filters with minimum preparation. A P-type detector is good for energies over 50 keV. An N-type or P-type planar (thin crystal) detector with a beryllium-end window is good for 5–80 keV energies using a thinner sample placed over the window.

H.3.4 Mass Spectrometry

Mass spectrometry (MS) techniques are frequently used to determine isotopic composition and measure isotopes at low concentrations in water and soil. MS is also used for radioactive waste source identification and characterization, as well as for isotopic ratio measurements for age determination. Because differences in isotopic masses are very small, and certain isotopes are very rare, this technique is unique because it is very sensitive (1 part per trillion [ppt] or less), which makes it suitable for measurements of medium- and long-lived radionuclides.

The MS technique is essentially based on measuring mass-to-charge ratio (m/z or m/e). It is initiated by ionizing materials to generate charged molecules or atoms and subsequently measuring magnetic resonance. The system involves the following steps: (1) conversion of the sample into a gaseous phase, (2) ionization through impaction by an ion beam, (3) separation based on magnetic resonance using an electromagnetic field analyzer, (4) ion detection and quantification, and (5) data processing instruments to process data into mass spectra. In brief, an MS system consists mainly of three key modules: ion source, mass analyzer, and detector.

Different types of mass spectrometric systems and techniques can be employed for radiological applications. For example, isotope ratio mass spectrometers usually employ a single magnet to bend a beam of ionized particles toward a series of cups designed to catch charged particles (e.g., Faraday cups), which convert particle impacts to electric current. Various ICP-MS units are commercially available, including single- and multi-collector magnetic-sector ICP-MS and quadrupole ICP-MS benchtop units. The other two types of mass spectrometers (i.e., accelerator mass spectrometers and thermal ionization mass spectrometers) are typically found at national laboratories and universities or institutes; are expensive; and require special facilities, including a clean-room environment for certain applications.

System: Inductively Coupled Plasma-Mass Spectrometer
Field/Laboratory: Laboratory
Radiation Detected: None (direct detection of isotopes based on mass-to-charge ratio)

Applicability to Site Surveys: The primary reasons for using ICP-MS include (1) instrument detection limits at or below the single ppt level for many of the periodic table elements, (2) an analytical working range of 9 orders of magnitude, (3) high productivity that is unsurpassed by any other techniques, and (4) readily achieved isotopic analysis.

Operation: The sample is injected into argon plasma as aerosol droplets, using a nebulizer and a spray chamber. After drying the aerosols, the plasma (e.g., ICP torch and radiofrequency coil generate the argon plasma, which serves as the ion source of the ICP-MS) dissociates the molecules, removes an electron from the components, and forms singly charged ions that are directed into the mass spectrometer filtering the ion masses. The interface links the atmospheric pressure ICP ion source to the high-vacuum mass spectrometer. The collision/reaction cell precedes the mass spectrometer and is used to remove interferences that can degrade the detection limits achieved. It is possible to have a cell that can be used both in the collision cell and reaction cell modes, which is referred to as a universal cell. Most commercial ICP-MS systems use quadrupole mass spectrometer systems, which scan the mass range. At any given time, only 1 m/z will be allowed to pass through the mass spectrometer from the entrance to the exit. A vacuum system provides high vacuum for ion optics, quadrupole, and detector. Ion optics guide the desired ions into the quadrupole, while ensuring that neutral species and photons are discarded from the ion beam. At the exit of the mass spectrometer, the ions strike the first dynode of an electron multiplier, which serves as the detector. The impact of the ions causes a cascade of electrons that are amplified to become a measurable pulse. MS software compares the intensities of sample measured pulses to pulses generated from known standards (e.g., making up a calibration curve) to determine the concentration of the element or isotope in the sample. The software also includes a data handling and system controller, which controls all aspects of instrument controls and data handling to obtain final concentration results. Isotopes can be readily analyzed, because for each element measured, it is typically necessary to measure just one isotope.

Specificity/Sensitivity: ICP-MS is one of the most versatile and sensitive MS techniques available. It can be used to determine the concentrations of more than 70 elements. The detection limit of the technique extends down to the ppb range in soils and to the ppt range in waters. ICP-MS can be used to supplement nuclear-decay emission counting techniques in the traditional radiochemical analysis laboratory.

For very long-lived radionuclides—those with half-lives more 10,000 years (e.g., $^{234/235/238}$U, $^{239/240/244}$Pu, ^{99}Tc, iodine-129 [^{129}I], neptunium-237 [^{237}Np])—ICP-MS may be faster and more sensitive than nuclear-decay emission analyses (i.e., systems designed to detect alpha, beta, or gamma emissions). In addition, sample preparation for ICP-MS can avoid some of the analyte separation and purification steps required for nuclear-decay emission analyses, providing an additional dimension of time savings. Another important feature of ICP-MS is its ability to provide isotopic distribution information (e.g., ^{238}U versus uranium-235 [^{235}U] and ^{239}Pu versus ^{240}Pu). This information is frequently useful in determining the age or origin of materials (using test methods in ASTM International [ASTM] standards ASTM C758, C759, and C799 [ASTM 2018a, 2018b, and 2019, respectively]). Typically, ICP-MS is sensitive enough to detect even femtograms (10^{-15} g) of a nuclide. Depending on the nuclide and required detection limit, the radioanalytical front-end chemistry may have to be conducted in a clean-room or clean-hood environment. In addition, high-purity reagents may be required for certain radionuclides

(e.g., uranium isotopes). For more sophisticated measurements at substantially higher cost, an ICP-MS with magnetic sector, instead of quadrupole, detection can be applied. Sector instruments are capable of resolving species of very similar mass. More typically, high-resolution instruments are employed for their higher signal-to-noise ratio, which should result in superior detection limits.

The isotopic discrimination capabilities of ICP-MS make possible the calibration technique known as “isotope dilution.” In this procedure, a sample is analyzed for one isotope after having been spiked with a different isotope of the same element (e.g., analysis of ^{235}U might involve spiking with uranium-233 [^{233}U]). The spiked sample is carried through all preparation and analysis steps; in this way, any matrix or procedural effects that might influence the ^{235}U signal will influence the ^{233}U signal to precisely the same extent. Final quantification relies on measuring the ratio of unknown (here the ^{235}U signal) to the known (^{233}U) signal. Isotope dilution is a way of generating highly precise and accurate data from a mass spectrometer and has been used in the characterization of many certified reference materials. For environmental sample analysis, the elements or radionuclide of interest are normally concentrated and isolated chemically.

System: Thermal Ionizing Mass Spectrometry
Field/Laboratory: Laboratory
Radiation Detected: None (direct detection of isotopes based on mass-to-charge ratio)

Applicability to Site Surveys: Similar to the standard MS technique, thermal ionizing mass spectrometry (TIMS) is frequently used to determine isotopic composition and measurement of isotopes at low concentrations in water and soil.

Operation: TIMS relies on ionization from a heated filament rather than from a plasma. It provides more precise measurements than routine quadrupole ICP-MS but requires substantially more operator involvement, leading to markedly reduced sample throughput compared to ICP-MS units. Because of the design of most TIMS units, a limit of four samples per batch can be analyzed sequentially without reloading another set of samples. TIMS systems exist at the national laboratories and the National Institute of Standards and Technology. These units are large and are usually considered too expensive for commercial laboratory operations. In addition, facilities housing TIMS may need a ventilation system equivalent to a Class 100 clean room, depending on the application. In some cases, the initial radioanalytical chemistry is conducted in a Class 100 clean room or hood. TIMS has been successfully applied to the analysis of ^{239}Pu, ^{240}Pu, ^{235}U, and ^{238}U in a variety of matrices. However, initial radioanalytical methods must be performed to isolate and concentrate the radionuclide from the initial sample. A radionuclide or isotopes in the concentrated solution would be electrodeposited on the filament used in the TIMS. For ^{239}Pu, Los Alamos National Laboratory (LANL) electrodeposits plutonium from a purified sample onto a TIMS filament with dihydrogen dinitrosulfatoplatinate. A larger quantity of platinum is then electrodeposited over the plutonium to provide a diffusion barrier that dissociates plutonium molecular species and provides high ionization efficiency.

Specificity/Sensitivity: Detection limits in the femtogram range are typical, resulting in a ^{239}Pu concentration of 600 nanobecquerels (nBq)/200 g sample. In a recent interlaboratory comparison study evaluating the capabilities of MS methods for the analysis of ultra-low quantities of ^{239}Pu and ^{240}Pu in urine, LANL's TIMS method had an estimated detection limit of 6 nBq/m^3 (microbecquerels [µBq]/L). For ^{240}Pu in the samples, the detection limit was estimated to be 20 µBq/L. LANL observed good precision (about 4 percent relative standard deviations) for ^{239}Pu test levels at 28 nBq/m^3 (µBq/L) and above. The ^{240}Pu measurements were less precise than the ^{239}Pu measurements, 11.9 percent and 21.2 percent respectively for 32 and 16 nBq/m^3 (µBq/L). TIMS has also been used to evaluate the isotopic ratio of ^{238}U/^{235}U in urine samples. Various MS techniques were used, including sector-field ICP-MS, quadrupole ICP-MS, and TIMS. The TIMS and quadrupole ICP-MS had similar detection limits: 0.1 pg for total uranium (based on ^{238}U) and about 15 pg for a ^{238}U/^{235}U ratio of 138 (natural abundance). The TIMS was able to measure ^{238}U/^{235}U ratios in ranges of 138:1–220:1 for three test levels of 25–100 nanograms (ng)/kg, 100–350 ng/kg, and greater than 350 ng/kg. The Multi-Agency Radiological Laboratory Analytical Protocols Manual (NRC 2004) contains more details.

System: Accelerator Mass Spectrometry
Field/Laboratory: Laboratory
Radiation Detected: None (direct detection of isotopes based on mass-to-charge ratio)

Applicability to Site Surveys: Accelerator mass spectrometry (AMS) differs from other MS techniques in that it depends on the acceleration of ions to extraordinarily high kinetic energy before MS analysis. A special merit of AMS among other MS methods is its power to separate a rare isotope from an abundant neighboring mass ("abundance sensitivity") (e.g., ^{14}C from carbon-12 [^{12}C]). The method suppresses molecular isobars completely and, in many cases, can separate atomic isobars (e.g., nitrogen-14 [^{14}N] from ^{14}C). Thus, it is possible for AMS to detect naturally occurring, long-lived radioisotopes, such as beryllium-10 (^{10}Be), chlorine-36 (^{36}Cl), aluminum-26 (^{26}Al), and ^{14}C, with typical isotopic abundance ranges from 10^{-12} to 10^{-18}. AMS can outperform the competing technique of decay counting for all isotopes when the half-life is long enough.

Operation: AMS techniques involve the acceleration of ions to extraordinarily high kinetic energy before MS analysis. The AMS system is technically sophisticated, expensive, and fairly large and requires extensive laboratory space and facilities. In AMS, negative ions—made in an ion source—are accelerated electrostatically through a field of millions of volts. The accelerated ions pass through a thin carbon film or a gas to destroy all molecular species. After passing through a low- or high-energy mass spectrometer and various filters, the resulting ions slow to a stop and dissipate their energy in a gas ionization detector. The identity of the individual ions is determined from the ions' rates of deceleration, with the lighter ions decelerating more rapidly than the heavier ions. For AMS analysis, solid samples in the 0.1–1 mg mass range are needed, which are pressed into sample holders. AMS has been used for geological, biological, and environmental applications for several decades.

Specificity/Sensitivity: In the 1980s, AMS replaced the traditional method of scintillation counting for precise radiocarbon dating. A ^{14}C detection limit of 200 nBq (5×10^4 atoms) is typical. Tritium, used extensively as a tracer in biological and oceanographic research, can be analyzed routinely by AMS with a detection limit of 20,000 nBq. AMS can be used to measure the following low-mass cosmogony radionuclides for earth science applications: ^{10}Be, ^{26}Al, silicon-32 (^{32}Si), ^{36}Cl, and calcium-41 (^{41}Ca). In addition, nickel-63 (^{63}Ni), ^{129}I, and $^{239/240}Pu$ are routinely analyzed by AMS at Lawrence Livermore National Laboratory. **Table H-1** provides the detection limits for these radionuclides (more details are available in NRC 2004, Chapter 15).

Table H-1 AMS Detection Limits

Nuclide	Detection Limit (nBq)	Detection Limit (10^5 atoms)
^{3}H	20,000	1
^{14}C	200	0.5
^{10}Be	4	3
^{26}Al	1	0.4
^{36}Cl	3	0.3
^{41}Ca	200	8
^{63}Ni	45,000	2
^{90}Sr	~100,000	~7
^{99}Tc	~30,000	~600
^{129}I	1	1
$^{239/240}Pu$	~1,000	~10

Source: McAninch et al. 1999

System: Flowing-Afterglow Mass Spectrometer
Field/Laboratory: Laboratory
Radiation Detected: None (direct detection of hydrogen isotopes at 1 ppt or less based on mass-to-charge ratio)

Applicability to Site Surveys: Flowing-afterglow mass spectrometry (FA-MS) is used for the determination of hydrogen isotopes in water and liquid environmental samples. FA-MS is a sensitive, quantitative MS analytical technique that offers online, real-time hydrogen-2 (^2H) abundance measurements in water vapor above aqueous liquids, including urine and serum. The flowing-afterglow technique can be used to identify and quantify the volatile organic compounds of a sample, as long as the fundamental ion chemistry is known. The commonly used ions are H_3O^+, O_2^+, and NO^+. All ions have drawbacks and advantages. Strategies that have been used to unequivocally identify the volatile organic compounds include gas chromatography coupled with flowing afterglow and using a complement of reagent ions.

Operation: FA-MS involves the production and flow of thermalized hydrated hydronium cluster ions in inert helium or argon carrier gas along a flow tube following the introduction of a humid air sample. These ions react in multiple collisions with water molecules; their isotopic compositions reach equilibrium, and the relative magnitudes of their isotopomers[3] are measured by a quadrupole mass spectrometer located downstream. In an FA-MS instrument, a weak microwave discharge is created in helium or argon carrier gas flowing through a narrow glass tube connected to a stainless steel flow tube. This forms flowing-afterglow plasma in the steel flow tube. The gas phase ion chemistry initiated by helium $(He)^+$ or argon $(Ar)^+$ ions reacting with trace amounts of water (H_2O) molecules results in the formation of H_3O^+ ions in the carrier gas. (Note that, here, H tacitly assumes the presence of both isotopes hydrogen-1 [^1H] and ^2H.) A sample of air/water vapor mixture to be analyzed is introduced at a known flow rate into the carrier gas, and its composite water molecules react with the H_3O^+ ions to form the $H_3O^+(H_2O)_{0,1,2,3}$ cluster ions and their analogous ^2H, oxygen-17 (^{17}O), and oxygen-18 (^{18}O) isotopic variants. The mixture of ions is sampled from the flowing swarm through a pinhole orifice located at the downstream end of the flow tube, and the ions are mass analyzed by a differentially pumped quadrupole mass spectrometer (pressure less than 10^{-4} Torr) with a single channel multiplier ion counting detector.

A typical mass spectrum will show clusters of peaks at an m/z of 19–21, 37–39, 55–57, and 73–75. The deuterium content of a water vapor sample introduced into the helium carrier gas can be determined from such spectra if the ^{17}O and ^{18}O contents of the ions are known. It is necessary to distinguish between the isotopic composition of the following three phases: the liquid water sample (designated by the subscript “liq”), the water vapor transferred from an aqueous sample headspace into the helium carrier gas (designated by the subscript “vap”), and the $H_3O^+(H_2O)_{0,1,2,3}$ ions and their isotopomers that comprise the ion swarm created in the carrier gas (designated by the subscript “ion”).

Specificity/Sensitivity: Detection limits are typically in the ppb range if there is a limited sample size, or ppt if there is an unlimited sample size.

[3] An isotopomer is an isotopic isomer, or an isomer with the same number of each isotopic atom but differing in their positions.

System: Time-of-Flight Mass Spectrometry
Field/Laboratory: Laboratory
Radiation Detected: None (identifies sample atoms or molecules by measuring their flight time)

Applicability to Site Surveys: Time-of-flight mass spectrometry (TOF-MS) identifies molecules and isotopes by measuring the time that sample molecules, all starting with the same kinetic energy, require to fly a known distance. As the sample molecules are moved about in a vacuum using electrical fields, it is necessary to ionize or induce charge on them. The molecules can be charged by bombarding them with electrons emitted from a filament. A well-known TOF-MS is the WBenchTOF-dx type, which commonly provides enhanced analytical performance in many fields, including environmental; petrochemical; food, flavor, and fragrance; metabolomics; homeland security; forensics and toxicology; and research and development applications.

Operation: As the name implies, a time-of-flight mass spectrometer identifies sample atoms or molecules by measuring their flight time. To allow the ions to fly through the flight path without hitting anything else, an ultra-high vacuum is maintained. In the typical vacuum inside a TOF-MS instrument, an ion can fly on average 600 m (0.37 mile) (mean-free path) before it will hit an air molecule. As the sample molecules are moved about in the vacuum, using electrical fields, it is necessary to ionize or put charge on them. The molecules can be charged by bombarding them with electrons emitted from a filament. When a molecule is hit, it is very likely to lose one or more of its electrons and therefore will be charged and become an ion.

Once the sample molecules are ionized, an electrical field accelerates them all to the same energy. As they all travel the same distance through the drift region, and their start velocity depends on their mass, measuring the time each ion takes to fly through the drift region is just proportional to the square root of their mass. In other words, the speed of an ion is dependent on its mass, with heavy ions having a lower velocity than light ones. All the accelerated ions then enter a field-free drift or a time-measurement region. The time measurement is done by the timing electronics, which applies a pulse of voltage to accelerate the ions and measures the time between this pulse of voltage and the ions impacting a detector located at the end of the ion flight path. The time will depend on the velocity of the ion and therefore is a measure of its m/z ratio.

Specificity/Sensitivity: Because ions of different mass will arrive at the detector sequentially, it is possible, with a perfect detector, to detect all the ion masses contained in each ion pulse. This is the fundamental reason why TOF-MS has extremely high overall sensitivity compared to other MS analyzer systems. Similarly, parallel ion detection means there is no inherent limitation on mass range, from unit mass upwards, as long as high-mass ions can be produced intact and the detector can register them.

System: Chemical Speciation Laser Ablation Mass Spectrometer
Field/Laboratory: Laboratory
Radiation Detected: None

Applicability to Site Surveys: Chemical speciation laser ablation MS has been successfully applied to the analysis of organic and inorganic molecular species in condensed material with high sensitivity and specificity.

Operation: Solids can be converted into aerosol particles that contain much of the molecular species information present in the original material. One way this is done is by laser excitation of one component of a solid mixture, which, when volatilized, carries along the other molecular species without fragmentation. Aerosol particles can be carried hundreds of feet without significant loss in a confined or directed air stream before analysis by MS. Some analytes of interest already exist in the form of aerosol particles. Laser ablation is also preferred over traditional means for the conversion of the aerosol particles into molecular ions for mass spectral analysis. Instrument manufacturers are working with scientists at national laboratories and universities to develop compact portable laser ablation MS instrumentation for field-based analyses.

Specificity/Sensitivity: This system can analyze soils and surfaces for organic and inorganic molecular species, with excellent detection capability. Environmental concentrations in the range of 10^{-9}–10^{-14} g/g can be determined, depending on environmental conditions. The system is highly effective when used by a skilled operator, but it is of limited use because of high costs. It may be possible to quantify an individual radionuclide if no other nuclides of that isotope are present in the sample matrix. Potential MDCs are 4×10^{-8} Bq/kg (1×10^{-9} pCi/g) for ^{238}U, 0.04 Bq/kg (10^{3} pCi/g) for ^{239}Pu, 4 Bq/kg (1 pCi/g) for ^{137}Cs, and 37 Bq/kg (10 pCi/g) for ^{60}Co.

H.3.5 Specialized Analysis

System: Kinetic Phosphorescence Analysis by Laser
Field/Laboratory: Laboratory (primary), Field (secondary)
Radiation Detected: Uranium or lanthanides

Applicability to Site Surveys: Several authors reported using a kinetic phosphorescence analysis by laser (KPA) unit for a variety of matrices that include water, urine, dissolved air filters, stack scrubber samples, soil, nuclear fuel reprocessing solutions, and synthetic lung fluid. An automated KPA has also been applied to monitor uranium in stack filters and probe washes at a nuclear facility. The KPA was adapted to incorporate an automatic sampler and syringe pump, permitting the unattended analysis of 60 samples. Methods were developed to eliminate interferences from inorganic and organic compounds. The reported detection limit was better than 1 ppb. Typical precision was about 5 percent.

Operation: KPA measures the rate of decay of the uranium or lanthanide characteristic emitting photon energy. The emitted light (e.g., photon) can be either fluorescence or phosphorescence. In either case, the detector is placed at right angles to the laser excitation. Fluorescent light is emitted immediately following ($<10^{-4}$ s) the excitation of the complex. With phosphorescence, however, the emitted light is delayed, following the excitation. This enables the light source to be pulsed and the measurement to occur when the laser source is off, thus providing improved signal-to-noise over fluorescence. The light signal from organic material will decay promptly (as light signals have a relatively short lifetime) and will not be available to the detector, which is gated off. A pulsed nitrogen dye laser (0.1–0.5 milliwatt range) often is used as the source, but other lasers can be used. Oxygen, chloride, and other ions can cause interference and may need to be removed before measurement. Measurements are taken at fixed time intervals.

In aqueous solution, the uranium or the lanthanide element is converted into complex form to reduce quenching and increase the lifetime of the complex. A good discussion describing the theoretical and functional aspects of a KPA unit and its application to the measurement of the uranyl ion in aqueous solutions has been reported by Brina and Miller (1992). The authors reported a detection limit for $(UO_2)^{+2}$ in aqueous solutions of 1 ng/L and a linear response from the detection limit to 5 mg/L. Several types of interference should be considered. The interferences can be differentiated into five categories: (1) light absorption agents, such as yellow solutions and ferric iron, (2) lumiphores, such as oils and humic acid, (3) quenching agents, including alcohols, halides (except fluoride), and certain metals, (4) competing reactions, and (5) hydrogen chloride. Chlorides interfere in the analysis by quenching the uranyl phosphorescence. Chemical interferences must be removed, or their concentration reduced significantly by dilution, to avoid inaccurate results.

Specificity/Sensitivity: KPA can be used to measure total uranium in water at concentrations greater than 0.05 microgram (µg)/L (0.05 ppb). Samples above the KPA dynamic range of about 400 ppm can be diluted with acid dilution ratio HNO_3 (1+19) prior to analysis. For the method described in ASTM D5174, “Standard Test Method for Trace Uranium in water by Pulsed-Laser Phosphorimetry” (ASTM 2023a), a 5 mL sample aliquant is pipetted into a glass vial, concentrated HNO_3 and H_2O_2 are added, and the solution is heated to near dryness. The residual material is dissolved in 1 mL of nitric acid that is diluted with 4 mL of H_2O, and a complexant is added. The 5 mL sample is analyzed by the KPA unit. Some reagents may have a relatively short shelf life and need to be ordered accordingly. An interlaboratory study conducted for ASTM D5174 measured bias below 0.5 percent and between-laboratory precision

(six laboratories) of 12 percent at a testing level of 2.25 ppb. For an individual laboratory, the relative precision was found to be about 4 percent at this level.

System: Instrumental Neutron Activation Analysis
Field/Laboratory: Laboratory
Radiation Detected: None (identifies sample atoms or molecules by irradiation by neutrons followed by emission and detection of gamma/beta)

Applicability to Site Surveys: This is a nondestructive, sensitive, multielement analytical technique commonly used for analysis of environmental samples, soils, water, and effluents with a distinct high sensitivity and low detection limit. Instrumental neutron activation analysis (INAA) is commonly used for the following:

- trace element analysis in rocks and minerals
- determination of sediment and soil compositions
- studies of partitioning of metals between phases in coal
- studies of origin of archaeological artifacts and correlations for archaeological analysis
- trace metals analysis in nanotech materials
- forensics applications
- determination of the chemistry of atmospheric aerosols
- distribution of metals in biological samples (e.g., tree rings)

Operation: The method is based on activation of elements by neutron bombardment, which causes elements in the sample to form radioactive isotopes. Following irradiation, the artificial radioisotopes decay through the emission of particles or, more importantly, gamma rays, which are characteristic of the element from which they were emitted. The radioactive emission and radioactive decay paths for each element are well known; therefore, based on these emission and decay characteristics and study of the emissions of the radioactive sample, concentrations of the elements can be determined. INAA can also be used to determine the activity of a radioactive sample.

About 50 mg of the sample is encapsulated in a vial made of either high-purity linear polyethylene or quartz. The sample and a standard are then packaged and irradiated in a suitable reactor at a constant, known neutron flux. A typical reactor used for activation uses U-fissions, providing a high neutron flux for the highest available sensitivities for most elements. The neutron flux from such a reactor is on the order of 10^{12}–10^{14} neutrons cm^{-2} s^{-1}, depending on the reactor power. In general, a 1 megawatt reactor has a peak thermal neutron flux of approximately 10^{13} neutrons cm^{-2} s^{-1}. The type of neutron generated is of relatively low kinetic energy, typically less than 0.5 electron volt. These neutrons are termed “thermal neutrons.” (If epithermal neutrons are required for the irradiation, then cadmium can be used to filter out the thermal neutrons.) Upon irradiation, a thermal neutron interacts with the target nucleus through a nonelastic collision, causing neutron capture. This collision forms a compound nucleus that is in an excited state. The excitation energy within the compound nucleus is formed from the binding energy of the thermal neutron with the target nucleus. This excited state is unfavorable, and the compound nucleus will almost instantaneously de-excite (transmutate) into a more stable configuration through the emission of a prompt particle and one or more characteristic prompt gamma photons. In most cases, this more stable configuration yields a radioactive nucleus. The newly formed radioactive nucleus now decays by the emission of both particles and one or more characteristic delayed gamma photons. This decay process is at a much slower rate than the initial de-excitation and is dependent on the unique half-life of the radioactive nucleus. These unique half-lives depend on the particular radioactive species and can range from fractions of a second to several years. Once irradiated, the sample is left for a specific decay period and then placed into a detector, which will measure the nuclear decay according to either the emitted particles or, more commonly, the emitted gamma rays.

Different types of neutron sources can be used, including a nuclear reactor; an actinoid, such as californium, which emits neutrons through spontaneous fission; an alpha source, such as radium or americium mixed with beryllium, which generates neutrons by a (α,^{12}C+n) reaction; and a deuterium-tritium fusion reaction in a gas discharge tube. Different detector types and configurations are used in INAA. Most are designed to detect the emitted gamma radiation. The most common types of gamma detectors encountered in INAA are the gas ionization, scintillation, and semiconductor types. Of these, the scintillation and semiconductor types are the most widely employed.

The major advantage of INAA is that it provides accurate results for large, bulk samples (tens of grams) without having to dissolve or digest the sample. INAA is an excellent complement to several advanced surface analysis techniques used for study of semiconductors, in that it can provide similar sensitivities on large, bulk silicon samples. One major disadvantage is that the technique requires access to a high-flux neutron source to obtain the required detection limit. As a result, the technique cannot be performed “in house” by industrial laboratories. A second disadvantage of INAA is the time required for the counting, which could take several days or more to achieve the required detection limits.

Specificity/Sensitivity: INAA can detect up to 74 elements depending on the experimental procedure, with minimum detection limits in the range of 0.1×10^{6}–1.0×10^{6} ng/g, depending on the element of concern.

H.4 Instrumentation Summary Tables

Tables H-2–H-8 offer brief overviews of each type of device described in this appendix, sorted by type of measurements taken.

Table H-2 Radiation Detectors with Applications to Alpha Surveys

System	Description	Application	Remarks
Alpha-beta scintillation survey meter (field)	<1 mg/cm^2 window, probe face area 50–100 cm^2.	Field measurement of presence or absence of alpha contamination on nonporous surfaces, swipes, and air filters, or on irregular surfaces if the degree of surface shielding is known.	Minimum detection capability is 10 cpm (1 cpm with headphones).
Gas-flow proportional counter (field)	A detector through which P-10 gas flows and that measures alpha and beta radiation; <1–10 mg/cm^2 window, probe face area 50–100 cm^2 for hand-held detectors and larger (e.g., 600 cm^2) if cart mounted.	Surface scanning, surface activity measurement, or field evaluation of swipes; serves as a screen to determine whether more nuclide-specific analyses are needed.	Natural radionuclides in samples can interfere with the detection of other radionuclides. The instrument requires P-10 gas.
Alpha spectroscopy with multichannel analyzer (laboratory)	A system using silicon diode surface barrier detectors for alpha energy identification and quantification.	Accurately identifies and measures the activity of multiple alpha radionuclides in a thin extracted sample of soil, water, or air filters.	Sample requires radiochemical separation or other preparation before counting.
Gas-flow proportional counter (laboratory)	Windowless (internal proportional) or with a <0.1 mg/cm^2 window, probe face area 10–20 cm^2; may have a second or guard detector to reduce background and minimum detectable activity.	Laboratory measurement of water, soil, air filter, and swipe samples.	The instrument requires P-10 gas. Windowless detectors can be contaminated.
Liquid scintillation spectrometer (laboratory and field)	Samples are mixed with LSC cocktail, and the radiation emitted causes light pulses with proportional intensity.	Laboratory analysis of alpha or beta emitters, including spectrometry capabilities. Small portable units available for measurements in the field.	Highly selective for alpha or beta radiation by pulse shape discrimination. Requires LSC cocktail.

System	Description	Application	Remarks
Low-resolution alpha spectrometer (laboratory)	Soil samples are measured in a vacuum chamber, and peak-fitting software estimates specific activity.	Laboratory analysis of alpha activity in soils.	Isotopes with energies closer than approximately 0.2 MeV cannot be separated.

Table H-3 Radiation Detectors with Applications to Beta Surveys

System	Description	Application	Remarks
Alpha-beta scintillation survey meter (field)	0.01 in. thick plastic scintillator added to an alpha scintillation survey meter.	Field measurement of presence or absence of beta-emitting radioactive material on nonporous surfaces, swipes, and air filters.	Most meters are capable of distinguishing between alpha and beta radiations in a mixed field.
Gas-flow proportional counter (field)	A detector through which P-10 gas flows and that measures alpha and beta radiation; <1–10 mg/cm^2 window, probe face area 50–100 cm^2 for hand-held detectors and larger (e.g., 600 cm^2) if cart mounted.	Surface scanning, surface activity measurement, or field evaluation of swipes; a screen to determine whether more nuclide-specific analyses are needed.	Natural radionuclides in samples can interfere with the detection of other radionuclides. The instrument requires P-10 gas but can be disconnected for hours.
Geiger-Mueller survey meter with beta pancake probe (field)	Thin 1.4 mg/cm^2 window detector, probe area 10–100 cm^2.	Surface scanning of personnel, working areas, equipment, and swipes for beta-emitting radioactive material; laboratory measurement of swipes when connected to a scaler.	Relatively high detection limit makes it of limited value in FSSs.
Gas-flow proportional counter (laboratory)	Windowless (internal proportional) or with a <0.1 mg/cm^2 window, probe face area 10–20 cm^2; may have a second or guard detector to reduce background and minimum detectable activity.	Laboratory measurement of water, air, and swipe samples.	The instrument requires P-10 gas. Windowless detectors can be contaminated.
Liquid scintillation counter (laboratory [primary] and field [secondary])	Samples mixed with LSC cocktail; radiation emitted causes light pulses with proportional intensity.	Laboratory analysis of alpha and beta emitters, including spectrometry capabilities.	The LSC process is highly selective for alpha and beta radiation by pulse shape discrimination.

Table H-4 Radiation Detectors with Applications to Gamma and X-Ray Surveys

System	Description	Application	Remarks
Hand-held ion chamber survey meter (field)	Ion chamber for measuring higher radiation levels than typical background.	Measuring true gamma exposure rate.	The meter is not very useful for site surveys because of high detection limit above background levels.
Hand-held PIC survey meter (field)	Ion chamber for measuring radiation at levels approaching typical background.	Measuring true gamma exposure rate with lower detection capability than the unpressurized ion chamber.	The meter is not very useful for site surveys because of high detection limit above background levels.
PIC (field)	A highly accurate, rugged, and stable ionization chamber.	Excellent for measuring gamma exposure rate during site remediation.	The chamber is used in conjunction with radionuclide identification equipment.
Survey meter with Geiger-Mueller gamma probe (field)	Thick-walled 30 mg/cm^2 detector.	Measuring radiation levels above 0.1 mR/h.	Its nonlinear energy response can be corrected by using an energy-compensated probe.
NaI survey meter (field)	Detector sizes typically 5 cm x 5 cm and 7.62 cm x 7.62 cm in size, with smaller sizes (2.54 cm x 2.54 cm) for enclosed micro-R meter.	Measuring low levels of environmental radiation.	Its energy response is not linear, so it should be calibrated for the energy field it will measure or have calibration factors developed by comparison with a PIC for a specific site.
Lanthanum bromide survey meter (field)	Comparable scintillation crystal thicknesses to NaI with high light output and fast decay time.	Useful for identifying radionuclides; produces semi-quantitative estimates of gamma-emitting isotopes in various media.	The meter offers improved energy resolution (3.0% at 661 keV) and counting efficiency as compared to NaI survey meters.
Cadmium zinc telluride detector (field)	Room temperature semi-conductor.	Useful for identifying radionuclides; produces semi-quantitative estimates of gamma-emitting isotopes in various media.	The detector offers excellent spectroscopic resolution and can process >10 million photons/s/mm^2.
Portable germanium multichannel analyzer system (field)	A pulsed or mechanically cooled version of a laboratory-based germanium detector and multichannel analyzer.	Excellent during characterization through FSS to identify and quantify the concentration of gamma ray-emitting radionuclides and in situ concentrations of soil and other media.	The analyzer requires a supply of liquid nitrogen or a mechanical cooling system, as well as highly trained operators.

System	Description	Application	Remarks
FIDLER probe with survey meter (field)	Thin crystals of NaI or cesium iodide.	Scanning of gamma/x-radiation from plutonium and americium.	FIDLER probes are most useful for determining the presence of plutonium and ^{241}Am. These isotopes have a complex of x-rays and gamma rays from 13–21 keV that have energies centered around 17 keV, and ^{241}Am has a gamma at 59 keV. There is an interference at 13 keV from both americium and uranium x-rays. The FIDLER cannot distinguish which isotope of plutonium is present.
Field x-ray fluorescence spectrometer (field)	Uses silicon or germanium semiconductor.	Determining fractional abundance of low-percentage metal atoms.	Ideal for sites containing metals that have strong x-ray emissions within 5–100 keV.
NaI detector with MCA (laboratory)	NaI crystal with a large range of sizes and shapes, connected to a PMT and MCA.	Laboratory gamma spectroscopy to determine the identity and concentration of gamma-emitting radionuclides in a sample.	The detector is sensitive for radioactive material in surface soil or groundwater. Analysis programs have difficulty if sample contains more than a few radionuclides.
Germanium detector with MCA (laboratory)	Intrinsic germanium semiconductor in P- or N-type configuration (with beryllium window for low photon energy detection).	Laboratory gamma spectroscopy to determine the identity and concentration of gamma-emitting radionuclides in a sample.	The detector is very sensitive for radioactive material in surface soil or groundwater. It is especially powerful when more than one radionuclide is present in a sample.
TLD (field and laboratory)	Crystals that are sensitive to gamma radiation.	Measuring cumulative radiation dose over a period of days to months.	The dosimeter requires special calibration to achieve high accuracy and reproducible results.

System	Description	Application	Remarks
ED (field and laboratory)	A silicon diode consisting of a junction of two types of semiconductors. When a positive voltage is applied between cathode and anode, electrons are pulled out of the depleted layer, and the current cannot then flow across the junction, except for the small leakage current. Radiation creates electron-hole pairs and a measurable current.	Identifying gamma levels slightly above natural background.	EDs are primarily used for measuring deep-dose gamma radiation. However, there are ED versions that can measure low-energy x-rays, beta particles, and neutrons. Gamma-sensitive EDs can measure from 0.1 mrem to 1,000 rem exposure and have an energy response from 60 keV to 6 MeV.
OSL dosimeter (field and laboratory)	Nondestructive analysis based on optical rather than thermal stimulation to release charge carriers from trapping centers.	Identifying gamma levels slightly above natural background.	OSL dosimeters are primarily sensitive to gamma radiation, but selected filter arrangements can be used to measure beta and x-ray radiation; OSLN can also be used for neutron radiation.

Table H-5 Radiation Detectors with Applications to Large Area Mobile Detector Arrays

System	Description	Application	Remarks
Aerial systems (field)	Array of high-efficiency detectors mounted on an airplane or helicopter that makes low-level flights.	Surveying very large areas to detect gamma radiation emitted from point or distributed sources.	Conversion of count rate to surface activity involves such parameters as type, number, and configuration of detectors; flight altitude and speed; isotopes of interest; soil density and moisture; and specific distribution.
Mobile detector array systems (field)	Array of detectors mounted to hand cart, trailer, all-terrain vehicle, or motor vehicle.	Surveying large areas to detect gamma radiation emitted from point or distributed sources.	Arrays typically consist of a series of NaI detectors of various sizes: 50 mm (2 in.) x 100 mm (4 in.) x 400 mm (16 in.), 50 mm (2 in.) x 100 mm (4 in.) x 400 mm (16 in.), 50 mm (2 in.) x 50 mm (2 in.), or FIDLERs.

Table H-6 Radiation Detectors with Applications to Radon Surveys

System	Description	Application	Remarks
Activated charcoal adsorption (field and laboratory)	Activated charcoal opened to the ambient air then gamma counted on a gamma scintillator or in a liquid scintillation counter.	Measuring radon concentration in indoor air.	The detector is deployed for 2–7 days. The MDC is 0.007–0.04 mBq/m^3 (Bq/L; 0.2–1.0 pCi/L).
Alpha track detector (field and laboratory)	A small piece of special plastic or film inside a small container. Damage tracks from alpha particles are chemically etched and tracks counted.	Measuring indoor or outdoor radon concentration in air.	Detection capability is a function of detector design and exposure duration and also a function of the size of the area being read by the laboratory. MDC is on the order of 0.04 mBq $m^{-3}d^{-1}$ (Bq L^{-1} d^{-1}; 1 pCi $L^{-1}d^{-1}$).
Continuous/ integrating radon monitor (field)	Air pump and scintillation cell or ionization chamber.	Tracking the real-time concentration of radon.	The system takes 1–4 hours to equilibrate before starting. The MDC is 0.004–0.2 mBq/m^3 (Bq/L; 0.1–5.0 pCi/L), depending on sample time.
Electret ion chamber (field)	A charged plastic vessel that can be opened for air to pass into.	Measuring short- or long-term radon concentration in indoor air.	A user must correct readings to account for gamma background concentration. The electret is sensitive to extremes of temperature and humidity. MDC is 0.007–0.02 mBq/m^3 (Bq/L) (0.2–0.5 pCi/L) for nominal 3-month measurement.
Large-area activated charcoal collector (field)	A canister containing activated charcoal is twisted into the surface and left for 24 hours.	Short-term radon flux measurements.	These collectors give an accurate short-term assessment of the radon gas surface emanation rate from a material. Exposures greater than 24 hours are not recommended because of atmospheric and surface moisture and temperature extremes, which may saturate the charcoal or affect charcoal efficiency.

Table H-7 Systems that Measure Atomic Mass or Emissions

System	Description	Application	Remarks
LA-ICP-AES (field)	Vaporizes and ionizes the surface material and measures emissions from the resulting atoms.	Live analysis of radioactive uranium and thorium concentrations in the field.	The spectrometer requires expensive equipment and skilled operators. LLD is 0.00041 Bq/g (0.11 pCi/g) for ^{232}Th and 0.012 Bq/g (0.33 pCi/g) for ^{238}U.
LA-ICP-MS (field)	Vaporizes and ionizes the surface material, then measures the mass of the resulting atoms.	Live analysis of radioactive uranium and thorium concentrations in the field.	The spectrometer requires expensive equipment and skilled operators. It is more sensitive than LA-ICP-AES. LLD is 0.6 Bq/g (15 pCi/g) for ^{230}Th.
Chemical speciation laser ablation/mass spectrometer (laboratory)	A laser changes the sample into an aerosol that it analyzes with a mass spectrometer.	Analyzing organic and inorganic species with high sensitivity and specificity.	Volatilized samples can be carried hundreds of feet to the analysis area.
ICP-MS (laboratory)	Direct detection of isotopes based on mass-to-charge-ratio.	Determine the concentrations of more than 70 elements.	The detection limit of the technique extends down to the ppb range in soils and to the ppt range in waters.
TIMS (laboratory)	Direct detection of isotopes based on mass-to-charge ratio.	Analyzing ^{239}Pu, ^{240}Pu, ^{235}U, and ^{238}U in a variety of matrices.	Similar to the standard MS technique, TIMS is frequently used to determine isotopic composition and measurement of isotopes at low concentrations in water and soil.
AMS (laboratory)	Direct detection of isotopes based on mass-to-charge ratio.	Detect naturally occurring, long-lived radioisotopes, such as ^{10}Be, ^{36}Cl, ^{26}Al, and ^{14}C, with typical isotopic abundance ranges from 10^{-12} to 10^{-18}.	AMS differs from other MS techniques in that it depends on acceleration of ions to extraordinarily high kinetic energy before MS analysis.
FA-MS (laboratory)	Direct detection of hydrogen isotopes at 1 ppt or less based on mass-to-charge ratio.	Determination of hydrogen isotopes in water and liquid environmental samples.	FA-MS is a sensitive quantitative MS analytical technique that offers online, real-time ^{2}H abundance measurements in water vapor above aqueous liquids, including urine and serum.

System	Description	Application	Remarks
TOF-MS (laboratory)	Identifies molecules by measuring the time that sample molecules, all starting with the same kinetic energy, require to fly a known distance.	Identifying molecules and isotopes by measuring the time that sample molecules, all starting with the same kinetic energy, require to fly a known distance.	—

Table H-8 Special Techniques and Equipment

System	Description	Application	Remarks
INAA (laboratory)	A nondestructive, sensitive, multielement analytical technique.	Analyzing environmental samples, soils, water, and effluents with a distinct high sensitivity and low detection limit.	INAA can detect up to 74 elements, depending on the experimental procedure, with minimum detection limits in the range of 0.1×10^{6}–1.0×10^{6} ng/g depending on element of concern.
Kinetic phosphorescence analysis by laser (laboratory [primary] and field [secondary])	Measures the rate of decay of the uranium or lanthanide characteristic emitting photon energy.	Measuring uranium or lanthanum in a variety of matrices.	The reported detection limit was better than 1 ppb, and typical precision was about 5%.

APPENDIX I
STATISTICAL TABLES AND PROCEDURES

I.1 Normal Distribution

Table I-1 Cumulative Normal Distribution Function $\Phi(z)$

z	*0.00*	*0.01*	*0.02*	*0.03*	*0.04*	*0.05*	*0.06*	*0.07*	*0.08*	*0.09*
0.00	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.10	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5674	0.5714	0.5753
0.20	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.30	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.40	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.50	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.60	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.70	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.80	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.90	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.00	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.10	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.20	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.30	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.40	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.50	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.60	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.70	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.80	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.90	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.00	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.10	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.20	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.30	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.40	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.50	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.60	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.70	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.80	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.90	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.00	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.10	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.20	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.30	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.40	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998

The cumulative normal distribution function values for negative values of z can be obtained from the relationship: $\Phi(-z) = 1 - \Phi(z)$ (i.e., the value in the table should[1] be subtracted from 1 to obtain the cumulative normal distribution function for negative values of z).

I.2 Sample Sizes for Statistical Tests

Table I-2 Sample Sizes for Sign Test, (α,β) or (β,α) (number of measurements to be performed in each survey unit)

Δ/σ	0.01 0.01	0.01 0.025	0.01 0.05	0.01 0.1	0.01 0.25	0.025 0.025	0.025 0.05	0.025 0.1	0.025 0.25	0.05 0.05	0.05 0.1	0.05 0.25	0.1 0.1	0.1 0.25	0.25 0.25
0.1	4095	3476	2984	2463	1704	2907	2459	1989	1313	2048	1620	1018	1244	725	345
0.2	1035	879	754	623	431	735	622	503	333	518	410	258	315	184	88
0.3	468	398	341	282	195	333	281	227	150	234	185	117	143	83	40
0.4	270	230	197	162	113	192	162	131	87	136	107	68	82	48	23
0.5	178	152	130	107	75	126	107	87	58	89	71	45	54	33	16
0.6	129	110	94	77	54	92	77	63	42	65	52	33	40	23	11
0.7	99	83	72	59	41	70	59	48	33	50	40	26	30	18	9
0.8	80	68	58	48	34	57	48	39	26	40	32	21	24	15	8
0.9	66	57	48	40	28	47	40	33	22	34	27	17	21	12	6
1.0	57	48	41	34	24	40	34	28	18	29	23	15	18	11	5
1.1	50	42	36	30	21	35	30	24	17	26	21	14	16	10	5
1.2	45	38	33	27	20	32	27	22	15	23	18	12	15	9	5
1.3	41	35	30	26	17	29	24	21	14	21	17	11	14	8	4
1.4	38	33	28	23	16	27	23	18	12	20	16	10	12	8	4
1.5	35	30	27	22	15	26	22	17	12	18	15	10	11	8	4
1.6	34	29	24	21	15	24	21	17	11	17	14	9	11	6	4
1.7	33	28	24	20	14	23	20	16	11	17	14	9	10	6	4
1.8	32	27	23	20	14	22	20	16	11	16	12	9	10	6	4
1.9	30	26	22	18	14	22	18	15	10	16	12	9	10	6	4
2.0	29	26	22	18	12	21	18	15	10	15	12	8	10	6	3
2.5	28	23	21	17	12	20	17	14	10	15	11	8	9	5	3
3.0	27	23	20	17	12	20	17	14	9	14	11	8	9	5	3

For $\Delta/\sigma > 3.0$, use the values on the row for $\Delta/\sigma = 3.0$.

[1] The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

Table I-3 Sample Sizes for Wilcoxon Rank Sum Test, (α,β) or (β,α) (number of measurements to be performed in the reference area and in each survey unit)

Δ/σ	0.01 0.01	0.01 0.025	0.01 0.05	0.01 0.1	0.01 0.25	0.025 0.025	0.025 0.05	0.025 0.1	0.025 0.25	0.05 0.05	0.05 0.1	0.05 0.25	0.1 0.1	0.1 0.25	0.25 0.25
0.1	5452	4627	3972	3278	2268	3870	3273	2646	1748	2726	2157	1355	1655	964	459
0.2	1370	1163	998	824	570	973	823	665	440	685	542	341	416	243	116
0.3	614	521	448	370	256	436	369	298	197	307	243	153	187	109	52
0.4	350	297	255	211	146	248	210	170	112	175	139	87	106	62	30
0.5	227	193	166	137	95	162	137	111	73	114	90	57	69	41	20
0.6	161	137	117	97	67	114	97	78	52	81	64	40	49	29	14
0.7	121	103	88	73	51	86	73	59	39	61	48	30	37	22	11
0.8	95	81	69	57	40	68	57	46	31	48	38	24	29	17	8
0.9	77	66	56	47	32	55	46	38	25	39	31	20	24	14	7
1.0	64	55	47	39	27	46	39	32	21	32	26	16	20	12	6
1.1	55	47	40	33	23	39	33	27	18	28	22	14	17	10	5
1.2	48	41	35	29	20	34	29	24	16	24	19	12	15	9	4
1.3	43	36	31	26	18	30	26	21	14	22	17	11	13	8	4
1.4	38	32	28	23	16	27	23	19	13	19	15	10	12	7	4
1.5	35	30	25	21	15	25	21	17	11	18	14	9	11	7	3
1.6	32	27	23	19	14	23	19	16	11	16	13	8	10	6	3
1.7	30	25	22	18	13	21	18	15	10	15	12	8	9	6	3
1.8	28	24	20	17	12	20	17	14	9	14	11	7	9	5	3
1.9	26	22	19	16	11	19	16	13	9	13	11	7	8	5	3
2.0	25	21	18	15	11	18	15	12	8	13	10	7	8	5	3
2.25	22	19	16	14	10	16	14	11	8	11	9	6	7	4	2
2.5	21	18	15	13	9	15	13	10	7	11	9	6	7	4	2
2.75	20	17	15	12	9	14	12	10	7	10	8	5	6	4	2
3.0	19	16	14	12	8	14	12	10	6	10	8	5	6	4	2

For $\Delta/\sigma > 3.0$, use the values on the row for $\Delta/\sigma = 3.0$.

Note that **Table I-3** is for the case in which the number of samples in the survey unit (n) is equal to the number of samples in the reference area (m). If n and m are not equal, refer to NUREG-1505.

I.3 Critical Values for the Sign Test

Table I-4 Critical Values for the Sign Test Statistic $S+(\alpha)$

N	*0.005*	*0.01*	*0.025*	*0.05*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*
4	4	4	4	4	3	3	3	2	2
5	5	5	5	4	4	3	3	3	2
6	6	6	5	5	5	4	4	3	3
7	7	6	6	6	5	5	4	4	3
8	7	7	7	6	6	5	5	4	4
9	8	8	7	7	6	6	5	5	4
10	9	9	8	8	7	6	6	5	5
11	10	9	9	8	8	7	6	6	5
12	10	10	9	9	8	7	7	6	6
13	11	11	10	9	9	8	7	7	6
14	12	11	11	10	9	9	8	7	7
15	12	12	11	11	10	9	9	8	7
16	13	13	12	11	11	10	9	9	8
17	14	13	12	12	11	10	10	9	8
18	14	14	13	12	12	11	10	10	9
19	15	14	14	13	12	11	11	10	9
20	16	15	14	14	13	12	11	11	10
21	16	16	15	14	13	12	12	11	10
22	17	16	16	15	14	13	12	12	11
23	18	17	16	15	15	14	13	12	11
24	18	18	17	16	15	14	13	13	12
25	19	18	17	17	16	15	14	13	12
26	19	19	18	17	16	15	14	14	13
27	20	19	19	18	17	16	15	14	13
28	21	20	19	18	17	16	15	15	14
29	21	21	20	19	18	17	16	15	14
30	22	21	20	19	19	17	16	16	15
31	23	22	21	20	19	18	17	16	15
32	23	23	22	21	20	18	17	17	16
33	24	23	22	21	20	19	18	17	16
34	24	24	23	22	21	19	19	18	17
35	25	24	23	22	21	20	19	18	17
36	26	25	24	23	22	21	20	19	18
37	26	26	24	23	22	21	20	19	18
38	27	26	25	24	23	22	21	20	19
39	27	27	26	25	23	22	21	20	19
40	28	27	26	25	24	23	22	21	20
41	29	28	27	26	25	23	22	21	20
42	29	28	27	26	25	24	23	22	21
43	30	29	28	27	26	24	23	22	21
44	30	30	28	27	26	25	24	23	22
45	31	30	29	28	27	25	24	23	22

N	*0.005*	*0.01*	*0.025*	*0.05*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*
46	32	31	30	29	27	26	25	24	23
47	32	31	30	29	28	26	25	24	23
48	33	32	31	30	28	27	26	25	24
49	33	33	31	30	29	27	26	25	24
50	34	33	32	31	30	28	27	26	25

For *N* greater than 50, the table (critical) value can be calculated from **Equation I-1:**

$$S+ = \frac{N}{2} + \frac{z}{2}\sqrt{N} \qquad \textbf{Equation I-1}$$

where z is the $(1-\alpha)$ percentile of a standard normal distribution, which can be found in **Table I-5** or in **Table N-2.**

Table I-5 Percentile of a Standard Normal Distribution

A	z
0.001	3.09
0.005	2.576
0.01	2.326
0.025	1.960
0.05	1.645
0.1	1.282

Other values can be found in **Table I-1.**

I.4 Critical Values for the Wilcoxon Rank Sum Test

Table I-6 Critical Values for the Wilcoxon Rank Sum Test

$m = 2$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43
$\alpha = 0.005$	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	40	42
$\alpha = 0.01$	7	9	11	13	15	17	19	21	23	25	27	28	30	32	34	36	38	39	41
$\alpha = 0.025$	7	9	11	13	15	17	18	20	22	23	25	27	29	31	33	34	36	38	40
$\alpha = 0.05$	7	9	11	12	14	16	17	19	21	23	24	26	27	29	31	33	34	36	38
$\alpha = 0.1$	7	8	10	11	13	15	16	18	19	21	22	24	26	27	29	30	32	33	35

$m = 3$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	56	59	62	65
$\alpha = 0.005$	12	15	18	21	24	27	30	32	35	38	40	43	46	48	51	54	57	59	62
$\alpha = 0.01$	12	15	18	21	24	26	29	31	34	37	39	42	45	47	50	52	55	58	60
$\alpha = 0.025$	12	15	18	20	22	25	27	30	32	35	37	40	42	45	47	50	52	55	57
$\alpha = 0.05$	12	14	17	19	21	24	26	28	31	33	36	38	40	43	45	47	50	52	54
$\alpha = 0.1$	11	13	16	18	20	22	24	27	29	31	33	35	37	40	42	44	46	48	50

$m = 4$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	18	22	26	30	34	38	42	46	49	53	57	60	64	68	71	75	78	82	86
$\alpha = 0.005$	18	22	26	30	33	37	40	44	47	51	54	58	61	64	68	71	75	78	81
$\alpha = 0.01$	18	22	26	29	32	36	39	42	46	49	52	56	59	62	66	69	72	76	79
$\alpha = 0.025$	18	22	25	28	31	34	37	41	44	47	50	53	56	59	62	66	69	72	75
$\alpha = 0.05$	18	21	24	27	30	33	36	39	42	45	48	51	54	57	59	62	65	68	71
$\alpha = 0.1$	17	20	22	25	28	31	34	36	39	42	45	48	50	53	56	59	61	64	67

$m = 5$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	25	30	35	40	45	50	54	58	63	67	72	76	81	85	89	94	98	102	107
$\alpha = 0.005$	25	30	35	39	43	48	52	56	60	64	68	72	77	81	85	89	93	97	101
$\alpha = 0.01$	25	30	34	38	42	46	50	54	58	62	66	70	74	78	82	86	90	94	98
$\alpha = 0.025$	25	29	33	37	41	44	48	52	56	60	63	67	71	75	79	82	86	90	94
$\alpha = 0.05$	24	28	32	35	39	43	46	50	53	57	61	64	68	71	75	79	82	86	89
$\alpha = 0.1$	23	27	30	34	37	41	44	47	51	54	57	61	64	67	71	74	77	81	84

$m = 6$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	33	39	45	51	57	63	67	72	77	82	88	93	98	103	108	113	118	123	128
$\alpha = 0.005$	33	39	44	49	54	59	64	69	74	79	83	88	93	98	103	107	112	117	122
$\alpha = 0.01$	33	39	43	48	53	58	62	67	72	77	81	86	91	95	100	104	109	114	118
$\alpha = 0.025$	33	37	42	47	51	56	60	64	69	73	78	82	87	91	95	100	104	109	113
$\alpha = 0.05$	32	36	41	45	49	54	58	62	66	70	75	79	83	87	91	96	100	104	108
$\alpha = 0.1$	31	35	39	43	47	51	55	59	63	67	71	75	79	83	87	91	94	98	102

$m = 7$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	42	49	56	63	69	75	81	87	92	98	104	110	116	122	128	133	139	145	151
$\alpha = 0.005$	42	49	55	61	66	72	77	83	88	94	99	105	110	116	121	127	132	138	143
$\alpha = 0.01$	42	48	54	59	65	70	76	81	86	92	97	102	108	113	118	123	129	134	139
$\alpha = 0.025$	42	47	52	57	63	68	73	78	83	88	93	98	103	108	113	118	123	128	133
$\alpha = 0.05$	41	46	51	56	61	65	70	75	80	85	90	94	99	104	109	113	118	123	128
$\alpha = 0.1$	40	44	49	54	58	63	67	72	76	81	85	90	94	99	103	108	112	117	121

$m = 8$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	52	60	68	75	82	89	95	102	109	115	122	128	135	141	148	154	161	167	174
$\alpha = 0.005$	52	60	66	73	79	85	92	98	104	110	116	122	129	135	141	147	153	159	165
$\alpha = 0.01$	52	59	65	71	77	84	90	96	102	108	114	120	125	131	137	143	149	155	161
$\alpha = 0.025$	51	57	63	69	75	81	86	92	98	104	109	115	121	126	132	137	143	149	154
$\alpha = 0.05$	50	56	62	67	73	78	84	89	95	100	105	111	116	122	127	132	138	143	148
$\alpha = 0.1$	49	54	60	65	70	75	80	85	91	96	101	106	111	116	121	126	131	136	141

$m = 9$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	63	72	81	88	96	104	111	118	126	133	140	147	155	162	169	176	183	190	198
$\alpha = 0.005$	63	71	79	86	93	100	107	114	121	127	134	141	148	155	161	168	175	182	188
$\alpha = 0.01$	63	70	77	84	91	98	105	111	118	125	131	138	144	151	157	164	170	177	184
$\alpha = 0.025$	62	69	76	82	88	95	101	108	114	120	126	133	139	145	151	158	164	170	176
$\alpha = 0.05$	61	67	74	80	86	92	98	104	110	116	122	128	134	140	146	152	158	164	170
$\alpha = 0.1$	60	66	71	77	83	89	94	100	106	112	117	123	129	134	140	145	151	157	162

$m = 10$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	75	85	94	103	111	119	128	136	144	152	160	167	175	183	191	199	207	215	222
$\alpha = 0.005$	75	84	92	100	108	115	123	131	138	146	153	160	168	175	183	190	197	205	212
$\alpha = 0.01$	75	83	91	98	106	113	121	128	135	142	150	157	164	171	178	186	193	200	207
$\alpha = 0.025$	74	81	89	96	103	110	117	124	131	138	145	151	158	165	172	179	186	192	199
$\alpha = 0.05$	73	80	87	93	100	107	114	120	127	133	140	147	153	160	166	173	179	186	192
$\alpha = 0.1$	71	78	84	91	97	103	110	116	122	128	135	141	147	153	160	166	172	178	184

$m = 11$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	88	99	109	118	127	136	145	154	163	171	180	188	197	206	214	223	231	240	248
$\alpha = 0.005$	88	98	107	115	124	132	140	148	157	165	173	181	189	197	205	213	221	229	237
$\alpha = 0.01$	88	97	105	113	122	130	138	146	153	161	169	177	185	193	200	208	216	224	232
$\alpha = 0.025$	87	95	103	111	118	126	134	141	149	156	164	171	179	186	194	201	208	216	223
$\alpha = 0.05$	86	93	101	108	115	123	130	137	144	152	159	166	173	180	187	195	202	209	216
$\alpha = 0.1$	84	91	98	105	112	119	126	133	139	146	153	160	167	173	180	187	194	201	207

$m = 12$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	102	114	125	135	145	154	164	173	183	192	202	210	220	230	238	247	256	266	275
$\alpha = 0.005$	102	112	122	131	140	149	158	167	176	185	194	202	211	220	228	237	246	254	263
$\alpha = 0.01$	102	111	120	129	138	147	156	164	173	181	190	198	207	215	223	232	240	249	257
$\alpha = 0.025$	100	109	118	126	135	143	151	159	168	176	184	192	200	208	216	224	232	240	248
$\alpha = 0.05$	99	108	116	124	132	140	147	155	165	171	179	186	194	202	209	217	225	233	240

$m = 12$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.1$	97	105	113	120	128	135	143	150	158	165	172	180	187	194	202	209	216	224	231

$m = 13$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	117	130	141	152	163	173	183	193	203	213	223	233	243	253	263	273	282	292	302
$\alpha = 0.005$	117	128	139	148	158	168	177	187	196	206	215	225	234	243	253	262	271	280	290
$\alpha = 0.01$	116	127	137	146	156	165	174	184	193	202	211	220	229	238	247	256	265	274	283
$\alpha = 0.025$	115	125	134	143	152	161	170	179	187	196	205	214	222	231	239	248	257	265	274
$\alpha = 0.05$	114	123	132	140	149	157	166	174	183	191	199	208	216	224	233	241	249	257	266
$\alpha = 0.1$	112	120	129	137	145	153	161	169	177	185	193	201	209	217	224	232	240	248	256

$m = 14$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	133	147	159	171	182	193	204	215	225	236	247	257	268	278	289	299	310	320	330
$\alpha = 0.005$	133	145	156	167	177	187	198	208	218	228	238	248	258	268	278	288	298	307	317
$\alpha = 0.01$	132	144	154	164	175	185	194	204	214	224	234	243	253	263	272	282	291	301	311
$\alpha = 0.025$	131	141	151	161	171	180	190	199	208	218	227	236	245	255	264	273	282	292	301
$\alpha = 0.05$	129	139	149	158	167	176	185	194	203	212	221	230	239	248	257	265	274	283	292
$\alpha = 0.1$	128	136	145	154	163	171	180	189	197	206	214	223	231	240	248	257	265	273	282

$m = 15$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	150	165	178	190	202	212	225	237	248	260	271	282	293	304	316	327	338	349	360
$\alpha = 0.005$	150	162	174	186	197	208	219	230	240	251	262	272	283	293	304	314	325	335	346
$\alpha = 0.01$	149	161	172	183	194	205	215	226	236	247	257	267	278	288	298	308	319	329	339
$\alpha = 0.025$	148	159	169	180	190	200	210	220	230	240	250	260	270	280	289	299	309	319	329
$\alpha = 0.05$	146	157	167	176	186	196	206	215	225	234	244	253	263	272	282	291	301	310	319
$\alpha = 0.1$	144	154	163	172	182	191	200	209	218	227	236	246	255	264	273	282	291	300	309

$m = 16$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	168	184	197	210	223	236	248	260	272	284	296	308	320	332	343	355	367	379	390
$\alpha = 0.005$	168	181	194	206	218	229	241	252	264	275	286	298	309	320	331	342	353	365	376
$\alpha = 0.01$	167	180	192	203	215	226	237	248	259	270	281	292	303	314	325	336	347	357	368
$\alpha = 0.025$	166	177	188	200	210	221	232	242	253	264	274	284	295	305	316	326	337	347	357
$\alpha = 0.05$	164	175	185	196	206	217	227	237	247	257	267	278	288	298	308	318	328	338	348
$\alpha = 0.1$	162	172	182	192	202	211	221	231	241	250	260	269	279	289	298	308	317	327	336

$m = 17$ $n =$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$\alpha = 0.001$	187	203	218	232	245	258	271	284	297	310	322	335	347	360	372	384	397	409	422
$\alpha = 0.005$	187	201	214	227	239	252	264	276	288	300	312	324	336	347	359	371	383	394	406
$\alpha = 0.01$	186	199	212	224	236	248	260	272	284	295	307	318	330	341	353	364	376	387	399
$\alpha = 0.025$	184	197	209	220	232	243	254	266	277	288	299	310	321	332	343	354	365	376	387
$\alpha = 0.05$	183	194	205	217	228	238	249	260	271	282	292	303	313	324	335	345	356	366	377
$\alpha = 0.1$	180	191	202	212	223	233	243	253	264	274	284	294	305	315	325	335	345	355	365

m = 18 *n* =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
α = 0.001	207	224	239	254	268	282	296	309	323	336	349	362	376	389	402	415	428	441	454
α = 0.005	207	222	236	249	262	275	288	301	313	326	339	351	364	376	388	401	413	425	438
α = 0.01	206	220	233	246	259	272	284	296	309	321	333	345	357	370	382	394	406	418	430
α = 0.025	204	217	230	242	254	266	278	290	302	313	325	337	348	360	372	383	395	406	418
α = 0.05	202	215	226	238	250	261	273	284	295	307	318	329	340	352	363	374	385	396	407
α = 0.1	200	211	222	233	244	255	266	277	288	299	309	320	331	342	352	363	374	384	395

m = 19 *n* =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
α = 0.001	228	246	262	277	292	307	321	335	350	364	377	391	405	419	433	446	460	473	487
α = 0.005	227	243	258	272	286	300	313	327	340	353	366	379	392	405	419	431	444	457	470
α = 0.01	226	242	256	269	283	296	309	322	335	348	361	373	386	399	411	424	437	449	462
α = 0.025	225	239	252	265	278	290	303	315	327	340	352	364	377	389	401	413	425	437	450
α = 0.05	223	236	248	261	273	285	297	309	321	333	345	356	368	380	392	403	415	427	439
α = 0.1	220	232	244	256	267	279	290	302	313	325	336	347	358	370	381	392	403	415	426

m = 20 *n* =	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
α = 0.001	250	269	286	302	317	333	348	363	377	392	407	421	435	450	464	479	493	507	521
α = 0.005	249	266	281	296	311	325	339	353	367	381	395	409	422	436	450	463	477	490	504
α = 0.01	248	264	279	293	307	321	335	349	362	376	389	402	416	429	442	456	469	482	495
α = 0.025	247	261	275	289	302	315	329	341	354	367	380	393	406	419	431	444	457	470	482
α = 0.05	245	258	271	284	297	310	322	335	347	360	372	385	397	409	422	434	446	459	471
α = 0.1	242	254	267	279	291	303	315	327	339	351	363	375	387	399	410	422	434	446	458

When using this table under Scenario A, *m* is the number of reference area samples and *n* is the number of survey unit samples. When using this table for Scenario B, the roles of *m* and *n* in this table are reversed. The parameter *m* is the number of survey unit samples, and the parameter *n* is the number of reference area samples.

Reject the null hypothesis if the test statistic (W_r) is greater than the table (critical) value.
For *n* or *m* greater than 20, if there are few or no ties, the table (critical) value can be calculated from **Equation I-2:**

$$W_r = \frac{m(n+m+1)}{2} + z\sqrt{\frac{nm(n+m+1)}{12}} \qquad \textbf{Equation I-2}$$

If there are many ties, it can be calculated from **Equation I-3:**

$$W_r = \frac{m(n+m+1)}{2} + z\sqrt{\frac{nm}{12}\left[(n+m+1) - \sum_{j=1}^{g}\frac{t_j(t_j^2-1)}{(n+m)(n+m-1)}\right]} \qquad \textbf{Equation I-3}$$

where *g* is the number of groups of tied measurements and t_j is the number of tied measurements in the j^{th} group. The value z is the $(1-\alpha)$ percentile of a standard normal distribution, which can be found in **Table I-5.**

I.5 Critical Values for the *t*-Distribution

Table I-7 Critical Values for the *t*-Distribution with a Confidence Interval of $1-\alpha$ and *v* degrees of freedom

$1-\alpha$ / v[1]	0.75	0.8	0.85	0.9	0.95	0.975	0.99	0.995	0.999	0.9995
100	0.677	0.846	1.042	1.291	1.661	1.984	2.365	2.626	3.174	3.391
200	0.676	0.844	1.040	1.286	1.653	1.972	2.346	2.601	3.132	3.340
300	0.676	0.843	1.039	1.285	1.650	1.968	2.339	2.593	3.118	3.324
400	0.676	0.843	1.038	1.284	1.649	1.966	2.336	2.589	3.111	3.316
500	0.675	0.843	1.038	1.284	1.648	1.965	2.334	2.586	3.107	3.311
600	0.675	0.843	1.038	1.283	1.648	1.964	2.333	2.585	3.104	3.307
700	0.675	0.843	1.038	1.283	1.648	1.964	2.332	2.583	3.102	3.305
800	0.675	0.843	1.038	1.283	1.647	1.963	2.332	2.582	3.101	3.303
900	0.675	0.843	1.038	1.283	1.647	1.963	2.331	2.582	3.100	3.302
1,000	0.675	0.842	1.037	1.283	1.647	1.963	2.331	2.581	3.099	3.301
2,500	0.675	0.842	1.037	1.282	1.646	1.961	2.328	2.578	3.094	3.295
5,000	0.675	0.842	1.037	1.282	1.646	1.961	2.328	2.577	3.092	3.293
10,000	0.675	0.842	1.037	1.282	1.646	1.961	2.327	2.577	3.092	3.292
25,000	0.675	0.842	1.037	1.282	1.645	1.961	2.327	2.577	3.091	3.291
50,000[2]	0.675	0.842	1.037	1.282	1.645	1.961	2.327	2.576	3.091	3.291

[1] For degrees of freedom not listed, round down to the next value of *v*.
[2] For values of *v* greater than 50,000, the change in the critical value becomes less significant and the critical value for 50,000 degrees of freedom may be used.

Note: Critical values can be calculated using the Microsoft Excel™ formula =T.INV(1-α,v).

I.6 Probability of Detecting an Elevated Area

Guidance for using **Table I-8** can be found in Gilbert 1987 and EPA 1989b. In **Table I-8**, *G* is the distance between grid points, and for an elliptical area of elevated activity, *L* is the length of the long axis of the ellipse, and *S* is the length of the short axis of the ellipse/*L*.

Table I-8 Risk that an Elevated Area with Length *L*/*G* and Shape *S* Will Not Be Detected and the Area (%) of the Elevated Area Relative to a Triangular Sample Grid Area of 0.866 G^2

	Shape Parameter, *S*																			
L*/*G	**0.10**		**0.20**		**0.30**		**0.40**		**0.50**		**0.60**		**0.70**		**0.80**		**0.90**		**1.00**	
	Risk	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**
0.01	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%
0.02	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%
0.03	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%
0.04	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	0.99	1%	0.99	1%
0.05	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%
0.06	1.00	<1%	1.00	<1%	1.00	<1%	0.99	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%
0.07	1.00	<1%	1.00	<1%	0.99	1%	0.99	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%
0.08	1.00	<1%	1.00	<1%	0.99	1%	0.99	<1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.98	2%	0.98	2%
0.09	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.98	2%	0.97	3%	0.97	3%
0.10	1.00	<1%	0.99	1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.97	3%	0.97	3%	0.96	4%
0.11	1.00	<1%	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.97	3%	0.96	4%	0.96	4%	0.96	4%
0.12	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.97	3%	0.96	4%	0.96	4%	0.95	5%	0.95	5%
0.13	0.99	1%	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.96	4%	0.96	4%	0.95	5%	0.94	6%	0.94	6%
0.14	0.99	1%	0.99	1%	0.98	2%	0.97	3%	0.96	4%	0.96	4%	0.95	5%	0.94	6%	0.94	6%	0.93	7%
0.15	0.99	1%	0.98	2%	0.98	2%	0.97	3%	0.96	4%	0.95	5%	0.94	6%	0.93	7%	0.93	7%	0.92	8%
0.16	0.99	1%	0.98	2%	0.97	3%	0.96	4%	0.95	5%	0.94	6%	0.94	7%	0.93	7%	0.92	8%	0.91	9%
0.17	0.99	1%	0.98	2%	0.97	3%	0.96	4%	0.95	5%	0.94	6%	0.93	7%	0.92	8%	0.91	9%	0.90	10%
0.18	0.99	1%	0.98	2%	0.96	4%	0.95	5%	0.94	6%	0.93	7%	0.92	8%	0.91	9%	0.89	11%	0.88	12%

	Shape Parameter, *S*																			
L/G	**0.10**		**0.20**		**0.30**		**0.40**		**0.50**		**0.60**		**0.70**		**0.80**		**0.90**		**1.00**	
0.19	0.99	1%	0.97	3%	0.96	4%	0.95	5%	0.93	7%	0.92	8%	0.91	9%	0.90	10%	0.88	12%	0.87	13%
0.20	0.99	1%	0.97	3%	0.96	4%	0.94	6%	0.93	7%	0.91	9%	0.90	10%	0.88	12%	0.87	13%	0.85	15%
0.21	0.98	2%	0.97	3%	0.95	5%	0.94	6%	0.92	8%	0.90	10%	0.89	11%	0.87	13%	0.86	14%	0.84	16%
0.22	0.98	2%	0.96	4%	0.95	5%	0.93	7%	0.91	9%	0.89	11%	0.88	12%	0.86	14%	0.84	16%	0.82	18%
0.23	0.98	2%	0.96	4%	0.94	6%	0.92	8%	0.90	10%	0.88	12%	0.87	13%	0.85	15%	0.83	17%	0.81	19%
0.24	0.98	2%	0.96	4%	0.94	6%	0.92	8%	0.90	10%	0.87	13%	0.85	15%	0.83	17%	0.81	19%	0.79	21%
0.25	0.98	2%	0.95	5%	0.93	7%	0.91	9%	0.89	11%	0.86	14%	0.84	16%	0.82	18%	0.80	20%	0.77	23%
0.26	0.98	2%	0.95	5%	0.93	7%	0.90	10%	0.88	12%	0.85	15%	0.83	17%	0.80	20%	0.78	22%	0.75	25%
0.27	0.97	3%	0.95	5%	0.92	8%	0.89	11%	0.87	13%	0.84	16%	0.81	19%	0.79	21%	0.76	24%	0.74	26%
0.28	0.97	3%	0.94	6%	0.91	9%	0.89	11%	0.86	14%	0.83	17%	0.80	20%	0.77	23%	0.74	26%	0.72	28%
0.29	0.97	3%	0.94	6%	0.91	9%	0.88	12%	0.85	15%	0.82	18%	0.79	21%	0.76	24%	0.73	27%	0.69	31%
0.30	0.97	3%	0.93	7%	0.90	10%	0.87	13%	0.84	16%	0.80	20%	0.77	23%	0.74	26%	0.71	29%	0.67	33%
0.31	0.97	3%	0.93	7%	0.90	10%	0.86	14%	0.83	17%	0.79	21%	0.76	24%	0.72	28%	0.69	31%	0.65	35%
0.32	0.96	4%	0.93	7%	0.89	11%	0.85	15%	0.81	19%	0.78	22%	0.74	26%	0.70	30%	0.67	33%	0.63	37%
0.33	0.96	4%	0.92	8%	0.88	12%	0.84	16%	0.80	20%	0.76	24%	0.72	28%	0.68	32%	0.64	36%	0.61	40%
0.34	0.96	4%	0.92	8%	0.87	13%	0.83	17%	0.79	21%	0.75	25%	0.71	29%	0.66	34%	0.62	38%	0.58	42%
0.35	0.96	4%	0.91	9%	0.87	13%	0.82	18%	0.78	22%	0.73	27%	0.69	31%	0.64	36%	0.60	40%	0.56	44%
0.36	0.95	5%	0.91	9%	0.86	14%	0.81	19%	0.76	24%	0.72	28%	0.67	33%	0.62	38%	0.58	42%	0.53	47%
0.37	0.95	5%	0.90	10%	0.85	15%	0.80	20%	0.75	25%	0.70	30%	0.65	35%	0.60	40%	0.55	45%	0.50	50%
0.38	0.95	5%	0.90	10%	0.84	16%	0.79	21%	0.74	26%	0.69	31%	0.63	37%	0.58	42%	0.53	47%	0.48	52%
0.39	0.94	6%	0.89	11%	0.83	17%	0.78	22%	0.72	28%	0.67	33%	0.61	39%	0.56	44%	0.50	50%	0.45	55%
0.40	0.94	6%	0.88	12%	0.83	17%	0.77	23%	0.71	29%	0.65	35%	0.59	41%	0.54	46%	0.48	52%	0.42	58%
0.41	0.94	6%	0.88	12%	0.82	18%	0.76	24%	0.70	30%	0.63	37%	0.57	43%	0.51	49%	0.45	55%	0.39	61%
0.42	0.94	6%	0.87	13%	0.81	19%	0.74	26%	0.68	32%	0.62	38%	0.55	45%	0.49	51%	0.42	58%	0.36	64%
0.43	0.93	7%	0.87	13%	0.80	20%	0.73	27%	0.66	34%	0.60	40%	0.53	47%	0.46	54%	0.40	60%	0.33	67%

	Shape Parameter, *S*																			
L/G	**0.10**		**0.20**		**0.30**		**0.40**		**0.50**		**0.60**		**0.70**		**0.80**		**0.90**		**1.00**	
	Risk	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**
0.44	0.93	7%	0.86	14%	0.79	21%	0.72	28%	0.65	35%	0.58	42%	0.51	49%	0.44	56%	0.37	63%	0.30	70%
0.45	0.93	7%	0.85	15%	0.78	22%	0.71	29%	0.63	37%	0.56	44%	0.49	51%	0.41	59%	0.34	66%	0.27	73%
0.46	0.92	8%	0.85	15%	0.77	23%	0.69	31%	0.62	38%	0.54	46%	0.46	54%	0.39	61%	0.31	69%	0.23	77%
0.47	0.92	8%	0.84	16%	0.76	24%	0.68	32%	0.60	40%	0.52	48%	0.44	56%	0.36	64%	0.28	72%	0.20	80%
0.48	0.92	8%	0.83	17%	0.75	25%	0.67	33%	0.58	42%	0.50	50%	0.41	59%	0.33	67%	0.25	75%	0.16	84%
0.49	0.91	9%	0.83	17%	0.74	26%	0.65	35%	0.56	44%	0.48	52%	0.39	61%	0.30	70%	0.22	78%	0.13	87%
0.50	0.91	9%	0.82	18%	0.73	27%	0.64	36%	0.55	45%	0.46	54%	0.37	63%	0.27	73%	0.18	82%	0.09	91%
0.51	0.91	9%	0.81	19%	0.72	28%	0.62	38%	0.53	47%	0.43	57%	0.34	66%	0.25	75%	0.15	85%	0.07	94%
0.52	0.90	10%	0.80	20%	0.71	29%	0.61	39%	0.51	49%	0.41	59%	0.32	69%	0.22	78%	0.13	88%	0.05	98%
0.53	0.90	10%	0.80	20%	0.70	31%	0.59	41%	0.49	51%	0.39	61%	0.29	71%	0.19	82%	0.10	92%	0.03	102%
0.54	0.89	11%	0.79	21%	0.68	32%	0.58	42%	0.47	53%	0.37	63%	0.27	74%	0.17	85%	0.08	95%	0.02	106%
0.55	0.89	11%	0.78	22%	0.67	33%	0.56	44%	0.46	55%	0.35	66%	0.24	77%	0.14	88%	0.06	99%	0.01	110%
0.56	0.89	11%	0.77	23%	0.66	34%	0.55	46%	0.44	57%	0.33	68%	0.22	80%	0.12	91%	0.04	102%	0.00	114%
0.57	0.88	12%	0.77	24%	0.65	35%	0.54	47%	0.42	59%	0.31	71%	0.20	83%	0.10	94%	0.02	106%	0.00	118%
0.58	0.88	12%	0.76	24%	0.64	37%	0.52	49%	0.40	61%	0.29	73%	0.18	85%	0.08	98%	0.01	110%	0.00	122%
0.59	0.87	13%	0.75	25%	0.63	38%	0.51	51%	0.39	63%	0.27	76%	0.16	88%	0.06	101%	0.00	114%	0.00	126%
0.60	0.87	13%	0.74	26%	0.62	39%	0.49	52%	0.37	65%	0.25	78%	0.14	91%	0.04	104%	0.00	118%	0.00	131%
0.61	0.87	13%	0.73	27%	0.60	40%	0.48	54%	0.35	67%	0.23	81%	0.12	94%	0.03	108%	0.00	121%	0.00	135%
0.62	0.86	14%	0.73	28%	0.59	42%	0.46	56%	0.34	70%	0.21	84%	0.10	98%	0.02	112%	0.00	126%	0.00	139%
0.63	0.86	14%	0.72	29%	0.58	43%	0.45	58%	0.32	72%	0.20	86%	0.09	101%	0.01	115%	0.00	130%	0.00	144%
0.64	0.85	15%	0.71	30%	0.57	45%	0.43	59%	0.30	74%	0.18	89%	0.07	104%	0.00	119%	0.00	134%	0.00	149%
0.65	0.85	15%	0.70	31%	0.56	46%	0.42	61%	0.29	77%	0.16	92%	0.06	107%	0.00	123%	0.00	138%	0.00	153%
0.66	0.84	16%	0.69	32%	0.55	47%	0.40	63%	0.27	79%	0.15	95%	0.05	111%	0.00	126%	0.00	142%	0.00	158%
0.67	0.84	16%	0.68	33%	0.53	49%	0.39	65%	0.25	81%	0.13	98%	0.03	114%	0.00	130%	0.00	147%	0.00	163%
0.68	0.84	17%	0.68	34%	0.52	50%	0.38	67%	0.24	84%	0.12	101%	0.02	117%	0.00	134%	0.00	151%	0.00	168%

	Shape Parameter, *S*																			
L*/*G	**0.10**		**0.20**		**0.30**		**0.40**		**0.50**		**0.60**		**0.70**		**0.80**		**0.90**		**1.00**	
	Risk	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**
0.69	0.83	17%	0.67	35%	0.51	52%	0.36	69%	0.22	86%	0.10	104%	0.01	121%	0.00	138%	0.00	155%	0.00	173%
0.70	0.83	18%	0.66	36%	0.50	53%	0.35	71%	0.21	89%	0.09	107%	0.01	124%	0.00	142%	0.00	160%	0.00	178%
0.71	0.82	18%	0.65	37%	0.49	55%	0.33	73%	0.20	91%	0.08	110%	0.00	128%	0.00	146%	0.00	165%	0.00	183%
0.72	0.82	19%	0.64	38%	0.48	56%	0.32	75%	0.18	94%	0.07	113%	0.00	132%	0.00	150%	0.00	169%	0.00	188%
0.73	0.81	19%	0.63	39%	0.46	58%	0.31	77%	0.17	97%	0.05	116%	0.00	135%	0.00	155%	0.00	174%	0.00	193%
0.74	0.81	20%	0.62	40%	0.45	60%	0.29	79%	0.15	99%	0.04	119%	0.00	139%	0.00	159%	0.00	179%	0.00	199%
0.75	0.80	20%	0.61	41%	0.44	61%	0.28	82%	0.14	102%	0.04	122%	0.00	143%	0.00	163%	0.00	184%	0.00	204%
0.76	0.80	21%	0.61	42%	0.43	63%	0.27	84%	0.13	105%	0.03	126%	0.00	147%	0.00	168%	0.00	189%	0.00	210%
0.77	0.79	22%	0.60	43%	0.42	65%	0.25	86%	0.12	108%	0.02	129%	0.00	151%	0.00	172%	0.00	194%	0.00	215%
0.78	0.79	22%	0.59	44%	0.40	66%	0.24	88%	0.10	110%	0.01	132%	0.00	154%	0.00	177%	0.00	199%	0.00	221%
0.79	0.78	23%	0.58	45%	0.39	68%	0.23	91%	0.09	113%	0.01	136%	0.00	158%	0.00	181%	0.00	204%	0.00	226%
0.80	0.78	23%	0.57	46%	0.38	70%	0.22	93%	0.08	116%	0.00	139%	0.00	163%	0.00	186%	0.00	209%	0.00	232%
0.81	0.77	24%	0.56	48%	0.37	71%	0.20	95%	0.07	119%	0.00	143%	0.00	167%	0.00	190%	0.00	214%	0.00	238%
0.82	0.77	24%	0.55	49%	0.36	73%	0.19	98%	0.06	122%	0.00	146%	0.00	171%	0.00	195%	0.00	220%	0.00	244%
0.83	0.76	25%	0.54	50%	0.35	75%	0.18	100%	0.05	125%	0.00	150%	0.00	175%	0.00	200%	0.00	225%	0.00	250%
0.84	0.76	26%	0.53	51%	0.33	77%	0.17	102%	0.05	128%	0.00	154%	0.00	179%	0.00	205%	0.00	230%	0.00	256%
0.85	0.75	26%	0.52	52%	0.32	79%	0.16	105%	0.04	131%	0.00	157%	0.00	183%	0.00	210%	0.00	236%	0.00	262%
0.86	0.74	27%	0.51	54%	0.31	80%	0.14	107%	0.03	134%	0.00	161%	0.00	188%	0.00	215%	0.00	241%	0.00	268%
0.87	0.74	27%	0.50	55%	0.30	82%	0.13	110%	0.02	137%	0.00	165%	0.00	192%	0.00	220%	0.00	247%	0.00	275%
0.88	0.73	28%	0.50	56%	0.29	84%	0.12	112%	0.02	140%	0.00	169%	0.00	197%	0.00	225%	0.00	253%	0.00	281%
0.89	0.73	29%	0.49	57%	0.28	86%	0.11	115%	0.01	144%	0.00	172%	0.00	201%	0.00	230%	0.00	259%	0.00	287%
0.90	0.72	29%	0.48	59%	0.27	88%	0.10	118%	0.01	147%	0.00	176%	0.00	206%	0.00	235%	0.00	264%	0.00	294%
0.91	0.72	30%	0.47	60%	0.26	90%	0.10	120%	0.01	150%	0.00	180%	0.00	210%	0.00	240%	0.00	270%	0.00	300%
0.92	0.71	31%	0.46	61%	0.25	92%	0.09	123%	0.00	154%	0.00	184%	0.00	215%	0.00	246%	0.00	276%	0.00	307%
0.93	0.71	31%	0.45	63%	0.24	94%	0.08	126%	0.00	157%	0.00	188%	0.00	220%	0.00	251%	0.00	282%	0.00	314%

	Shape Parameter, *S*																			
L*/*G	**0.10**		**0.20**		**0.30**		**0.40**		**0.50**		**0.60**		**0.70**		**0.80**		**0.90**		**1.00**	
	Risk	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**	**Risk**	**Area**
0.94	0.70	32%	0.44	64%	0.23	96%	0.07	128%	0.00	160%	0.00	192%	0.00	224%	0.00	256%	0.00	288%	0.00	321%
0.95	0.69	33%	0.43	65%	0.22	98%	0.07	131%	0.00	164%	0.00	196%	0.00	229%	0.00	262%	0.00	295%	0.00	327%
0.96	0.69	33%	0.42	67%	0.21	100%	0.06	134%	0.00	167%	0.00	201%	0.00	234%	0.00	267%	0.00	301%	0.00	334%
0.97	0.68	34%	0.41	68%	0.20	102%	0.05	137%	0.00	171%	0.00	205%	0.00	239%	0.00	273%	0.00	307%	0.00	341%
0.98	0.68	35%	0.40	70%	0.19	105%	0.05	139%	0.00	174%	0.00	209%	0.00	244%	0.00	279%	0.00	314%	0.00	348%
0.99	0.67	36%	0.40	71%	0.18	107%	0.04	142%	0.00	178%	0.00	213%	0.00	249%	0.00	284%	0.00	320%	0.00	356%
1.00	0.67	36%	0.39	73%	0.17	109%	0.04	145%	0.00	181%	0.00	218%	0.00	254%	0.00	290%	0.00	326%	0.00	363%

I.7 Test Statistics for the Quantile Test

Table I-9 Values of r and k for the Quantile Test When α Is Approximately 0.01

m	Number of Survey Unit Measurements, *n*																			
	5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
5	**r,k** ***α***		11,11 0.008	13,13 0.015	16,16 0.014	19,19 0.013	22,22 0.013	25,25 0.013	28,28 0.012											**r,k** ***α***
10		6,6 0.005	7,7 0.013	9,9 0.012	11,11 0.011	13,13 0.01	14,14 0.014	16,16 0.013	18,18 0.012	19,19 0.015	21,21 0.014	23,23 0.013	25,25 0.012	26,26 0.015	28,28 0.014	30,30 0.013				
15	3,3 0.009	7,6 0.007	6,6 0.008	7,7 0.011	8,8 0.014	10,10 0.009	11,11 0.011	12,12 0.013	13,13 0.014	15,15 0.011	16,16 0.012	17,17 0.013	18,18 0.014	19,19 0.015	21,21 0.012	22,22 0.013	23,23 0.014	24,24 0.015	26,26 0.013	27,27 0.013
20	6,4 0.005	4,4 0.008	5,5 0.009	6,6 0.01	7,7 0.011	8,8 0.011	9,9 0.011	10,10 0.011	11,11 0.011	12,12 0.011	13,13 0.011	14,14 0.012	15,15 0.012	16,16 0.012	17,17 0.012	18,18 0.012	19,19 0.012	19,19 0.015	20,20 0.015	21,21 0.015
25	4,3 0.009	7,5 0.012	4,4 0.015	5,5 0.013	6,6 0.011	7,7 0.01	8,8 0.009	9,9 0.009	9,9 0.014	10,10 0.012	11,11 0.011	12,12 0.011	12,12 0.015	13,13 0.014	14,14 0.013	15,15 0.012	16,16 0.011	16,16 0.014	17,17 0.014	18,18 0.013
30	4,3 0.006	3,3 0.012	4,4 0.009	5,5 0.007	6,6 0.006	6,6 0.012	7,7 0.01	8,8 0.008	8,8 0.013	9,9 0.011	10,10 0.009	10,10 0.013	11,11 0.011	12,11 0.014	12,12 0.013	13,13 0.012	14,14 0.011	14,14 0.014	15,15 0.012	15,15 0.015
35	2,2 0.013	3,3 0.008	4,4 0.006	4,4 0.014	5,5 0.01	6,6 0.007	6,6 0.012	7,7 0.009	7,7 0.014	8,8 0.011	9,9 0.009	9,9 0.013	10,10 0.01	10,10 0.014	11,11 0.011	11,11 0.015	12,12 0.012	13,13 0.011	13,13 0.013	14,14 0.012
40	2,2 0.01	3,3 0.006	7,5 0.013	4,4 0.01	5,5 0.006	5,5 0.012	6,6 0.008	6,6 0.013	7,7 0.009	7,7 0.013	8,8 0.01	8,8 0.014	9,9 0.011	9,9 0.014	10,10 0.011	10,10 0.014	11,11 0.012	11,11 0.014	12,12 0.012	12,12 0.014
45	2,2 0.008	6,4 0.008	3,3 0.013	4,4 0.007	4,4 0.014	5,5 0.008	5,5 0.014	6,6 0.009	6,6 0.013	7,7 0.009	7,7 0.013	8,8 0.009	8,8 0.012	9,9 0.009	9,9 0.012	10,10 0.009	10,10 0.012	10,10 0.015	11,11 0.012	11,11 |0.014
50		4,3 0.013	3,3 0.01	4,4 0.005	4,4 0.01	5,5 0.006	5,5 0.01	5,5 0.015	6,6 0.009	6,6 0.013	7,7 0.009	7,7 0.012	8,8 0.009	8,8 0.011	8,8 0.014	9,9 0.011	9,9 0.013	10,10 0.01	10,10 0.012	10,10 0.015
55		4,3 0.010	3,3 0.008	7,5 0.013	4,4 0.008	4,4 0.014	5,5 0.007	5,5 0.011	6,6 0.007	6,6 0.01	6,6 0.014	7,7 0.009	7,7 0.012	8,8 0.008	8,8 0.01	8,8 0.013	9,9 0.009	9,9 0.012	9,9 0.014	10,10 0.011
60		4,3 0.008	3,3 0.007	3,3 0.014	4,4 0.006	4,4 0.011	5,5 0.006	5,5 0.009	5,5 0.013	6,6 0.007	6,6 0.01	6,6 0.014	7,7 0.009	7,7 0.011	7,7 0.014	8,8 0.01	8,8 0.012	8,8 0.015	9,9 0.01	9,9 0.013
65		4,3 0.007	3,3 0.006	3,3 0.012	6,5 0.006	4,4 0.009	4,4 0.013	5,5 0.007	5,5 0.01	5,5 0.014	6,6 0.008	6,6 0.011	6,6 0.014	7,7 0.009	7,7 0.011	7,7 0.014	8,8 0.009	8,8 0.011	8,8 0.014	9,9 0.01
70		2,2 0.014	6,4 0.008	3,3 0.01	7,5 0.013	4,4 0.007	4,4 0.011	5,5 0.005	5,5 0.008	5,5 0.011	5,5 0.015	6,6 0.008	6,6 0.011	6,6 0.014	7,7 0.009	7,7 0.011	7,7 0.013	8,8 0.009	8,8 0.011	8,8 0.013
75		2,2 0.013	4,3 0.014	3,3 0.008	3,3 0.014	4,4 0.006	4,4 0.009	4,4 0.013	5,5 0.006	5,5 0.009	5,5 0.012	6,6 0.007	6,6 0.009	6,6 0.011	6,6 0.014	7,7 0.009	7,7 0.011	7,7 0.013	8,8 0.008	8,8 0.01
80		2,2 0.011	4,3 0.012	3,3 0.007	3,3 0.012	6,5 0.006	4,4 0.008	4,4 0.011	5,5 0.005	5,5 0.007	5,5 0.01	5,5 0.013	6,6 0.007	6,6 0.009	6,6 0.012	6,6 0.014	7,7 0.009	7,7 0.01	7,7 0.013	7,7 0.015

m	Number of Survey Unit Measurements, *n*																			
	5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
85		2,2 0.01	4,3 0.01	3,3 0.006	3,3 0.011	7,5 0.013	4,4 0.006	4,4 0.009	4,4 0.013	5,5 0.006	5,5 0.008	5,5 0.011	5,5 0.014	6,6 0.008	6,6 0.01	6,6 0.012	6,6 0.014	7,7 0.008	7,7 0.01	7,7 0.012
90			4,3 0.009	3,3 0.005	3,3 0.009	3,3 0.014	4,4 0.005	4,4 0.008	4,4 0.011	5,5 0.005	5,5 0.007	5,5 0.009	5,5 0.012	5,5 0.015	6,6 0.008	6,6 0.01	6,6 0.012	6,6 0.014	7,7 0.008	7,7 0.019
95			4,3 0.008	6,4 0.008	3,3 0.008	3,3 0.013	6,5 0.005	4,4 0.007	4,4 0.01	4,4 0.013	5,5 0.006	5,5 0.008	5,5 0.01	5,5 0.013	6,6 0.007	6,6 0.008	6,6 0.01	6,6 0.012	6,6 0.014	7,7 0.008
100	**r,k** ***α***		4,3 0.007	4,3 0.014	3,3 0.007	3,3 0.011	7,5 0.013	4,4 0.006	4,4 0.008	4,4 0.011	4,4 0.015	5,5 0.007	5,5 0.009	5,5 0.011	5,5 0.013	6,6 0.007	6,6 0.008	6,6 0.01	6,6 0.012	6,6 0.014

n: number of survey unit measurements; *m*: number of reference area measurements; r: number of samples from the combined reference and survey unit that defines the quantile of interest; k: maximum number of samples in the largest r values of the combined samples that are allowed to be from the survey unit to achieve the acceptable Type I decision error (α error); α: alpha error, or false positive error

Note: While the targeted alpha error is provided in the table caption, the table provides the exact alpha error based on *n*, *m*, r, and k.

Table I-10 Values of r and k for the Quantile Test When α Is Approximately 0.025

m	Number of Survey Unit Measurements, *n*																			
	5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
5	**r,k** ***α***		9,9 0.03	12,12 0.024	15,15 0.021	17,17 0.026	20,20 0.024	22,22 0.028	25,25 0.025											**r,k** ***α***
10		7,6 0.029	6,6 0.028	8,8 0.022	9,9 0.029	11,11 0.024	12,12 0.029	14,14 0.025	17,17 0.025	18,18 0.029	20,20 0.026	21,21 0.029	23,23 0.026	24,24 0.029	26,26 0.026	27,27 0.029				
15	11,5 0.030	6,5 0.023	5,5 0.021	6,6 0.024	7,7 0.026	8,8 0.027	9,9 0.028	10,10 0.029	11,11 0.030	13,13 0.022	15,15 0.023	14,14 0.023	16,16 0.024	17,17 0.025	18,18 0.025	19,19 0.026	21,21 0.021	21,21 0.027	22,22 0.027	23,23 0.027
20	8,4 0.023	3,3 0.030	4,4 0.026	5,5 0.024	6,6 0.022	7,7 0.020	12,11 0.021	13,12 0.024	9,9 0.028	10,10 0.026	11,11 0.024	12,12 0.023	13,13 0.022	13,13 0.029	14,14 0.027	15,15 0.026	16 16 0.025	17,17 0.024	17,17 0.029	18,18 0.028
25	2,2 0.023	8,5 0.027	6,5 0.021	7,6 0.023	5,5 0.025	6,6 0.020	10,9 0.026	7,7 0.027	8,8 0.023	13,12 0.027	9,9 0.027	10,10 0.024	11,11 0.022	11,11 0.028	12,12 0.025	13,13 0.023	13,13 0.028	14,14 0.025	15,15 0.023	15,15 0.028
30	6,3 0.026	6,4 0.026	9,6 0.026	4,4 0.021	7,6 0.029	5,5 0.026	9,8 0.024	6,6 0.029	7,7 0.023	12,11 0.021	8,8 0.025	9,9 0.021	9,9 0.027	10,10 0.023	10,10 0.029	11,11 0.025	11,11 0.030	12,12 0.026	13,13 0.023	13,13 0.027
35	7,3 0.030	4,3 0.030	3,3 0.023	6,5 0.02	4,4 0.026	10,8 0.022	5,5 0.027	9,8 0.024	6,6 0.027	7,7 0.020	7,7 0.027	8,8 0.021	8,8 0.027	9,9 0.022	9,9 0.027	10,10 0.022	10,10 0.027	11,11 0.022	11,11 0.027	12,12 0.023
40	3,2 0.029	4,3 0.022	8,5 0.028	11,7 0.025	6,5 0.028	4,4 0.03	10,8 0.026	5,5 0.027	9,8 0.023	6,6 0.026	10,9 0.028	7,7 0.024	12,11 0.02	8,8 0.023	8,8 0.029	9,9 0.022	9,9 0.027	10,10 0.021	10,10 0.026	11,11 0.021

m	Number of Survey Unit Measurements, *n*																			
	5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
45	3,2 0.023	8,4 0.029	6,4 0.036	3,3 0.026	8,6 0.021	4,4 0.023	7,6 0.025	5,5 0.020	5,5 0.028	9,8 0.023	6,6 0.024	10,9 0.026	7,7 0.022	7,7 0.027	8,8 0.020	8,8 0.025	8,8 0.030	9,9 0.023	9,9 0.027	10,10 0.021
50		2,2 0.025	6,4 0.022	3,3 0.021	11,7 0.027	6,5 0.026	4,4 0.026	7,6 0.028	5,5 0.021	5,5 0.028	9,8 0.022	6,6 0.023	6,6 0.029	7,7 0.02	7,7 0.025	12,11 0.020	8,8 0.022	8,8 0.026	13,12 0.027	9,9 0.023
55		2,2 0.022	4,3 0.029	8,5 0.028	3,3 0.028	8,6 0.021	4,4 0.020	4,4 0.029	10,8 0.021	5,5 0.022	5,5 0.028	9,8 0.022	6,6 0.092	6,6 0.028	10,9 0.029	7,7 0.023	7,7 0.027	12,11 0.023	8,8 0.023	8,8 0.027
60		14,5 0.022	4,3 0.024	8,5 0.021	3,3 0.023	11,7 0.029	6,5 0.024	4,4 0.023	7,6 0.023	10,8 0.024	5,5 0.023	5,5 0.029	9,8 0.022	6,6 0.022	6,6 0.027	10,9 0.027	7,7 0.021	7,7 0.025	7,7 0.030	8,8 0.021
65		6,3 0.028	7,4 0.021	6,4 0.025	10,6 0.025	3,3 0.029	8,6 0.021	6,5 0.029	4,4 0.026	7,6 0.026	10,8 0.026	5,5 0.023	5,5 0.029	9,8 0.022	6,6 0.021	6,6 0.026	10,9 0.026	7,7 0.020	7,7 0.024	7,7 0.028
70		6,3 0.024	2,2 0.029	6,4 0.021	8,5 0.028	3,3 0.025	13,8 0.026	6,5 0.023	4,4 0.022	4,4 0.028	7,6 0.028	10,8 0.027	5,5 0.024	5,5 0.029	9,8 0.022	6,6 0.021	6,6 0.025	6,6 0.029	10,9 0.030	7,7 0.022
75		11,4 0.022	2,2 0.026	4,3 0.028	8,5 0.022	3,3 0.022	9,6 0.028	8,6 0.021	6,5 0.027	4,4 0.024	7,6 0.023	7,6 0.030	10,8 0.029	5,5 0.024	5,5 0.029	9,8 0.021	6,6 0.021	6,6 0.024	6,6 0.028	10,9 0.028
80		7,3 0.028	2,2 0.024	4,3 0.024	6,4 0.028	10,6 0.024	3,3 0.027	13,8 0.027	6,5 0.023	4,4 0.020	4,4 0.026	7,6 0.024	10,8 0.023	5,5 0.027	5,5 0.025	5,5 0.029	9,8 0.021	6,6 0.020	6,6 0.024	6,6 0.027
85		3,2 0.029	2,2 0.021	4,3 0.021	6,4 0.023	8,5 0.028	3,3 0.023	9,6 0.030	8,6 0.020	6,5 0.026	4,4 0.022	4,4 0.028	7,6 0.026	10,8 0.024	5,5 0.021	5,5 0.025	5,5 0.029	9,8 0.021	6,6 0.020	6,6 0.023
90			5,3 0.020	11,5 0.027	9,5 0.023	8,5 0.023	3,3 0.021	3,3 0.028	13,8 0.028	6,5 0.022	6,5 0.029	4,4 0.024	4,4 0.029	7,6 0.028	10,8 0.026	5,5 0.022	5,5 0.025	5,5 0.030	9,8 0.021	9,8 0.025
95			10,4 0.029	2,2 0.029	4,3 0.028	6,4 0.029	10,6 0.023	3,3 0.025	11,7 0.026	8,6 0.02	6,5 0.025	4,4 0.021	4,4 0.026	7,6 0.024	7,6 0.029	10,8 0.027	5,5 0.022	5,5 0.026	5,5 0.030	9,8 0.021
100	**r,k** ***α***		6,3 0.029	2,2 0.027	4,3 0.025	6,4 0.025	8,5 0.028	3,3 0.022	3,3 0.029	13,8 0.028	6,5 0.022	6,5 0.028	4,4 0.023	4,4 0.027	7,6 0.025	10,8 0.022	10,8 0.028	5,5 0.022	5,5 0.026	5,5 0.030

n: number of survey unit measurements; *m*: number of reference area measurements; r: number of samples from the combined reference and survey unit that defines the quantile of interest; k: maximum number of samples in the largest r values of the combined samples that are allowed to be from the survey unit to achieve the acceptable Type I decision error (α error); α: alpha error, or false positive error

Note: While the targeted alpha error is provided in the table caption, the table provides the exact alpha error based on *n*, *m*, r, and k.

Table I-11 Values of r and k for the Quantile Test When α Is Approximately 0.05

m	Number of Survey Unit Measurements, *n*																			
	5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
5	**r,k** ***α***		8,8 0.051	10,10 0.057	13 13 0.043	15 15 0.048	17,17 0.051	19,19 0.054	21,21 0.056											**r,k** ***α***
10		4,4 0.043	5,5 0.057	14,12 0.045	8,8 0.046	9,9 0.052	10,10 0.058	12,12 0.046	13,13 0.05	14,14 0.054	15,15 0.057	17,17 0.049	18,18 0.052	19,1 0.055	20,20 0.057	21,21 0.059	23,23 0.053			
15	2,2 0.053	3,3 0.052	4,4 0.05	5,5 0.048	6,6 0.046	7,7 0.045	8,8 0.052	9,9 0.043	9,9 0.06	10,10 0.057	11,11 0.055	12,12 0.054	13,13 0.052	14,14 0.051	15,15 0.05	16,16 0.049	16,16 0.058	17,17 0.057	18,18 0.056	19,19 0.055
20	9,4 0.04	8,5 0.056	6,5 0.04	4,4 0.053	5,5 0.043	9,8 0.052	6,6 0.056	7,7 0.048	8,8 0.043	8,8 0.057	9,9 0.051	10,10 0.046	10,10 0.057	11,11 0.052	12,12 0.048	12,12 0.057	13,13 0.053	14,14 0.049	14,14 0.057	15,15 0.054
25	6,3 0.041	6,4 0.043	3,3 0.046	6,5 0.052	4,4 0.055	5,5 0.041	5,5 0.059	6,6 0.046	11,10 0.042	7,7 0.05	8,8 0.042	8,8 0.053	9,9 0.045	9,9 0.055	10,10 0.048	11,11 0.042	11,11 0.05	11,11 0.058	12,12 0.052	12,12 0.06
30	3,2 0.047	2,2 0.058	10,6 0.052	3,3 0.058	11,8 0.045	4,4 0.056	8,7 0.044	5,5 0.054	6,6 0.04	6,6 0.053	7,7 0.041	7,7 0.052	8,8 0.042	8,8 0.051	9,9 0.042	9,9 0.05	9,9 0.059	10,10 0.049	10,10 0.057	11,11 0.049
35	8,3 0.046	2,2 0.045	6,4 0.058	3,3 0.043	6,5 0.041	4,4 0.04	4,4 0.057	8,7 0.043	5,5 0.051	9,8 0.052	6,6 0.047	6,6 0.057	7,7 0.043	7,7 0.053	8,8 0.041	8,8 0.049	8,8 0.057	9,9 0.046	9,9 0.053	10,10 0.044
40	4,2 0.055	5,3 0.048	4,3 0.057	10,6 0.059	3,3 0.053	6,5 0.048	4,4 0.043	4,4 0.058	8,7 0.042	5,5 0.048	9,8 0.047	6,6 0.042	6,6 0.051	11,10 0.042	7,7 0.045	7,7 0.053	8,8 0.041	8,8 0.048	8,8 0.055	9,9 0.043
45	4,2 0.045	9,4 0.047	2,2 0.059	8,5 0.052	3,3 0.042	8,6 0.041	6,5 0.054	4,4 0.045	4,4 0.058	8,7 0.041	5,5 0.046	5,5 0.057	9,8 0.056	6,6 0.047	6,6 0.055	11,10 0.046	7,7 0.047	7,7 0.054	8,8 0.041	8,8 0.047
50		6,3 0.051	2,2 0.05	6,4 0.051	12,7 0.05	3,3 0.049	8,6 0.049	6,5 0.059	4,4 0.047	4,4 0.059	8,7 0.041	5,5 0.045	5,5 0.054	9,8 0.051	6,6 0.043	6,6 0.050	6,6 0.058	7,7 0.041	7,7 0.048	7,7 0.054
55		3,2 0.059	2,2 0.043	4,3 0.056	8,5 0.058	3,3 0.041	5,4 0.041	6,5 0.046	9,7 0.042	4,4 0.048	4,4 0.059	8,7 0.04	5,5 0.043	5,5 0.052	9,8 0.048	6,6 0.04	6,6 0.047	6,6 0.054	11,10 0.043	7,7 0.043
60		3,2 0.052	5,3 0.052	4,3 0.046	6,4 0.059	3,3 0.035	3,3 0.047	8,6 0.043	6,5 0.051	9,7 0.046	4,4 0.049	4,4 0.059	13,10 0.052	5,5 0.042	5,5 0.05	5,5 0.058	9,8 0.054	6,6 0.044	6,6 0.05	6,6 0.056
65		3,2 0.045	5,3 0.043	2,2 0.053	6,4 0.048	10,6 0.05	3,3 0.04	3,3 0.052	6,5 0.041	6,5 0.055	4,4 0.042	4,4 0.05	4,4 0.06	13,10 0.052	5,5 0.041	5,5 0.048	5,5 0.055	9,8 0.051	6,6 0.041	6,6 0.047
70		8,3 0.057	9,4 0.048	2,2 0.047	4,3 0.055	8,5 0.05	5,4 0.041	3,3 0.046	3,3 0.057	6,5 0.045	6,5 0.058	4,4 0.043	4,4 0.051	4,4 0.06	13,10 0.051	5,5 0.041	5,5 0.047	5,5 0.054	9,8 0.048	9,8 0.057
75		8,3 0.049	6,3 0.056	2,2 0.043	4,3 0.047	6,4 0.054	10,6 0.053	3,3 0.04	3,3 0.051	8,6 0.044	6,5 0.049	9,7 0.041	4,4 0.044	4,4 0.052	5,5 0.06	13,10 0.051	8,7 0.047	5,5 0.046	5,5 0.052	5,5 0.058
80		4,2 0.059	6,3 0.048	5,3 0.053	2,2 0.055	6,4 0.046	8,5 0.055	5,4 0.041	3,3 0.045	3,3 0.055	6,5 0.041	6,5 0.052	9,7 0.043	4,4 0.045	4,4 0.053	7,6 0.058	13,10 0.051	8 7 0.046	5,5 0.045	5,5 0.051
85		4,2 0.054	3,2 0.058	5,3 0.047	2,2 0.05	4,3 0.054	4,3 0.048	10,6 0.056	5,4 0.049	3,3 0.049	3,3 0.059	6,5 0.044	6,5 0.055	9,7 0.046	4,4 0.046	4,4 0.053	7,6 0.059	10,8 0.06	8,7 0.045	5,5 0.044
90			3,2 0.053	5,3 0.041	2,2 0.046	6,4 0.059	6,4 0.051	8,5 0.058	5,4 0.042	3,3 0.044	3,3 0.053	8,6 0.045	6,5 0.047	6,5 0.058	4,4 0.04l	4,4 0.047	4,4 0.054	7,6 0.059	10,8 0.06	8,7 0.041

m	Number of Survey Unit Measurements, *n*																			
	5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
95			3,2 0.048	9,4 0.048	2,2 0.042	2,2 0.056	4,3 0.059	8,5 0.05	10,6 0.058	5,4 0.048	3,3 0.048	3,3 0.056	6,5 0.041	6,5 0.05	9,7 0.040	4,4 0.042	4,4 0.048	4,4 0.054	7,6 0.59	10,8 0.059
100	**r,k** ***α***		3,2 0.044	6,3 0.057	5,3 0.054	2,2 0.052	4,3 0.053	6,4 0.056	10,6 0.049	5,4 0.043	3,3 0.043	3,3 0.051	3,3 0.059	6,5 0.044	6,5 0.053	9,7 0.042	4,4 0.043	4,4 0.049	4,4 0.055	7,6 0.059

n: number of survey unit measurements; *m*: number of reference area measurements; r: number of samples from the combined reference and survey unit that defines the quantile of interest; k: maximum number of samples in the largest r values of the combined samples that are allowed to be from the survey unit to achieve the acceptable Type I decision error (α error); α: alpha error, or false positive error

Note: While the targeted alpha error is provided in the table caption, the table provides the exact alpha error based on *n*, *m*, r, and k.

Table I-12 Values of r and k for the Quantile Test When α Is Approximately 0.10

M	Number of Survey Unit Measurements, *n*																			
	5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
5	**r,k** ***α***		7,7 0.083	8,8 0.116	10,10 0.109	12,12 0.104	14,14 0.1	15,15 0.117	17,17 0.112											**r,k** ***α***
10		3,3 0.105	4,4 0.108	5,5 0.109	6,6 0.109	7,7 0.109	8,8 0.109	9,9 0.109	10,10 0.109	11,11 0.109	12,12 0.109	13,13 0.109	14,14 0.109	15,15 0.109	16,16 0.109	17,12 0.109	18,18 0.109			
15	9,4 0.098	10,6 0.106	3,3 0.112	4,4 0.093	5,5 0.081	5,5 0.117	6,6 0.102	7,7 0.092	7,7 0.118	8,8 0.106	9,9 0.098	9,9 0.118	10,10 0.109	11,11 0.101	11,11 0.118	12,12 0.11	13,13 0.104	13,13 0.118	14,14 0.111	15,15 0.106
20	3,2 0.091	2,2 0.103	5,4 0.093	3,3 0.115	4,4 0.085	4,4 0.119	5,5 0.093	10,9 0.084	6,6 0.099	7,7 0.083	7,7 0.102	8,8 0.088	8,8 0.105	9,9 0.092	9,9 0.107	10,10 0.095	10,11 0.108	11,11 0.098	11,11 0.110	12,12 0.100
25	4,2 0.119	7,4 0.084	8,5 0.112	3,3 0.08	3,3 0.117	4,4 0.08	4,4 0.107	8,7 0.108	5,5 0.101	10,9 0.088	6,6 0.096	6,6 0.114	7,7 0.093	7,7 0.108	8,8 0.091	8,8 0.104	8,8 0.117	9,9 0.1	9,9 0.112	10,10 0.098
30	4,2 0.089	5,3 0.089	2,2 0.106	14,8 0.111	3,3 0.088	3,3 0.119	9,7 0.116	4,4 0.100	8,7 0.093	5,5 0.088	5,5 0.106	6,6 0.08	6,6 0.095	6,6 0.11	7,7 0.087	7,7 0.1	7,7 0.113	8,8 0.092	8,8 0.103	8,8 0.115
35	5,2 0.109	3,2 0.119	2,2 0.086	6,4 0.12	5,4 0.091	3,3 0.093	3,3 0.12	9,7 0.112	4,4 0.094	4,4 0.114	8,7 0.107	5,5 0.094	5,5 0.11	6,6 0.081	6,6 0.094	6,6 0.107	6,6 0.12	7,7 0.094	7,7 0.105	7,7 0.116
40	5,2 0.087	3,2 0.098	5,3 0.119	2,2 0.107	12,7 0.109	5,4 0.102	3,3 0.097	6,5 0.100	9,7 0.109	4,4 0.09	4,4 0.107	8,7 0.097	5,5 0.086	5,5 0.099	5,5 0.112	6,6 0.082	6,6 0.093	6,6 0.104	6,6 0.116	7,7 0.089
45	6,2 0.103	3,2 0.082	5,3 0.094	2,2 0.091	6,4 0.115	7,5 0.086	5,4 0.112	3,3 0.1	6,5 0.101	9,7 0.107	4,4 0.087	4,4 0.102	4,4 0.117	8,7 0.107	5,5 0.091	5,5 0.103	5,5 0.115	6,6 0.083	6,6 0.093	6,6 0.103
50		7,3 0.083	9,4 0.115	7,4 0.097	2,2 0.108	10,6 0.112	5,4 0.09	3,3 0.084	3,3 0.103	6,5 0.102	9,7 0.105	4,4 0.084	4,4 0.098	4,4 0.112	8,7 0.099	5,5 0.084	5,5 0.95	5,5 0.105	5,5 0.116	6,6 0.083

M	Number of Survey Unit Measurements, *n*																		
	5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
55		4,2 0.109	3,2 0.114	5,3 0.114	2,2 0.095	6,4 0.112	14,8 0.111	5,4 0.098	3,3 0.088	3,3 0.104	6,5 0.103	9,7 0.104	4,4 0.082	4,4 0.095	4,4 0.107	4,4 0.12	8,7 0.107	5,5 0.088	5,5 0.098	5,5 0.108
60		4,2 0.095	3,2 0.100	5,3 0.097	2,2 0.084	2,2 0.109	8,5 0.119	5,4 0.082	5,4 0.105	3,3 0.091	3,3 0.106	6,5 0.103	9,7 0.102	4,4 0.081	4,4 0.092	4,4 0.103	4,4 0.115	8,7 0.1	5,5 0.083	5,5 0.092
65		4,2 0.084	3,2 0.089	5,3 0.082	7,4 0.090	2,2 0.097	6,4 0.110	12,7 0.113	5,4 0.089	5,4 0.111	3,3 0.093	3,3 0.108	6,5 0.104	9,7 0.101	7,6 0.084	4,4 0.090	4,4 0.100	4,4 0.110	8,7 0.094	8,7 0.107
70		5,2 0.115	7,3 0.101	9,4 0.106	5,3 0.112	2,2 0.088	2,2 0.109	8,5 0.114	7,5 0.081	5,4 0.096	3,3 0.083	3,3 0.096	3,3 0.109	6,5 0.104	9,7 0.191	7,6 0.082	4,4 0.088	4,4 0.097	4,4 0.107	4,4 0.117
75		5,2 0.103	7,3 0.088	3,2 0.111	5,3 0.098	7,4 0.101	2,2 0.099	2,2 0.119	10,6 0.117	5,4 0.083	5,4 0.102	3,3 0.085	3,3 0.098	3,3 0.110	6,5 0.105	9,7 0.1	7,6 0.081	4,4 0.086	4,4 0.095	4,4 0.104
80		5,2 0.093	4,2 0.116	3,2 0.101	5,3 0.086	7,4 0.086	2,2 0.09!	2,2 0.109	8,5 0.111	14,8 0.11	5,4 0.089	5,4 0.107	3,3 0.088	3,3 0.099	3,3 0.111	6,5 0.105	6,5 0.12	9,7 0.116	4,4 0.084	4,4 0.093
85		5,2 0.084	4,2 0.106	3,2 0.092	9,4 117	5,3 0.111	2,2 0.083	2,2 0.101	2,2 0.118	10,6 0.112	7,5 0.084	5,4 0.094	5,4 0.111	3,3 0.09	3,3 0.101	3,3 0.112	6,5 0.105	6,5 0.119	9,7 0.114	4,4 0.083
90			4,2 0.097	3,2 0.085	3,2 0.119	5,3 0.099	7,4 0.095	2,2 0.093	2,2 0.109	8,5 0.108	12,7 0.114	5,4 0.083	5,4 0.099	3,3 0.082	3,3 0.092	3,3 0.102	3,3 0.113	6,5 0.105	6,5 0.119	9,7 0.113
95			4,2 0.089	7,3 100	3,2 0.11	5,3 0.089	7,4 0.084	2,2 0.086	2,2 0.102	2,2 0.117	10,6 0.08	14,8 0.117	5,4 0.088	5,4 0.103	3,3 0.084	3,3 0.094	3,3 0.103	3,3 0.113	6,5 0.106	6,5 0.118
100	**r,k** ***α***		4,2 0.082	7,3 0.090	3,2 0.102	5,3 0.080	5,3 0.109	2,2 0.080	2,2 0.095	2,2 0.110	6,4 0.118	12,7 0.109	7,5 0.086	5,4 0.093	5,4 0.08	3,3 0.086	3,3 0.095	3,3 0.104	3,3 0.114	6,5 0.106

n: number of survey unit measurements; *m*: number of reference area measurements; r: number of samples from the combined reference and survey unit that defines the quantile of interest; k: maximum number of samples in the largest r values of the combined samples that are allowed to be from the survey unit to achieve the acceptable Type I decision error (α error); α: alpha error, or false positive error

Note: While the targeted alpha error is provided in the table caption, the table provides the exact alpha error based on *n*, *m*, r, and k.

I.8 Random Numbers

Table I-13 1,000 Random Numbers Uniformly Distributed between Zero and One

Random Numbers Uniformly Distributed between Zero and One*									
0.163601	0.647423	0.555548	0.248859	0.259801	0.718368	0.305020	0.812482	0.601951	0.973160
0.934196	0.951102	0.979831	0.132364	0.157808	0.040605	0.997626	0.896462	0.360578	0.443218
0.054552	0.965257	0.999181	0.172627	0.583713	0.852958	0.116336	0.748483	0.058602	0.738495
0.972409	0.241889	0.799991	0.926726	0.585505	0.453993	0.877990	0.947022	0.910821	0.388081
0.556401	0.621126	0.293328	0.984335	0.366531	0.912588	0.733824	0.092405	0.717362	0.423421
0.625153	0.838711	0.196153	0.630553	0.867808	0.957094	0.830218	0.783518	0.141557	0.444997
0.527330	0.124034	0.351792	0.161947	0.688925	0.140346	0.553577	0.890058	0.470457	0.566196
0.826643	0.673286	0.550827	0.885295	0.690781	0.371540	0.108632	0.090765	0.618443	0.937184
0.296068	0.891272	0.392367	0.649633	0.261410	0.523221	0.769081	0.358794	0.924341	0.167665
0.848882	0.083603	0.274621	0.268003	0.272254	0.017727	0.309463	0.445986	0.244653	0.944564
0.779276	0.484461	0.101393	0.995100	0.085164	0.611426	0.030270	0.494982	0.426236	0.270225
0.095038	0.577943	0.186239	0.267852	0.786070	0.208937	0.184565	0.826397	0.256825	0.489034
0.011672	0.844846	0.443407	0.915087	0.275906	0.883009	0.243728	0.865552	0.796671	0.314429
0.215993	0.476035	0.354717	0.883172	0.840666	0.393867	0.374810	0.222167	0.114691	0.596046
0.982374	0.101973	0.683995	0.730612	0.548200	0.084302	0.145212	0.337680	0.566173	0.592776
0.860868	0.794380	0.819422	0.752871	0.158956	0.317468	0.062387	0.909843	0.779089	0.648967
0.718917	0.696798	0.463655	0.762408	0.823097	0.843209	0.368678	0.996266	0.542048	0.663842
0.800735	0.225556	0.398048	0.437067	0.642698	0.144068	0.104212	0.675095	0.318953	0.648478
0.915538	0.711742	0.232159	0.242961	0.327863	0.156608	0.260175	0.385141	0.681475	0.978186
0.975506	0.652654	0.928348	0.513444	0.744095	0.972031	0.527368	0.494287	0.602829	0.592834
0.435196	0.272807	0.452254	0.793464	0.817291	0.828245	0.407518	0.441518	0.358966	0.619741
0.692512	0.368151	0.821543	0.583707	0.802354	0.133831	0.569521	0.474516	0.437608	0.961559
0.678823	0.930602	0.657348	0.025057	0.294093	0.499623	0.006423	0.290613	0.325204	0.044439
0.642075	0.029842	0.289042	0.891009	0.813844	0.973093	0.952871	0.361623	0.709933	0.466955
0.174285	0.863244	0.133649	0.773819	0.891664	0.246417	0.272407	0.517658	0.132225	0.795514
0.951401	0.921291	0.210993	0.369411	0.196909	0.054389	0.364475	0.716718	0.096843	0.308418
0.186824	0.005407	0.310843	0.998118	0.725887	0.143171	0.293721	0.841304	0.661969	0.409622
0.105673	0.026338	0.878006	0.105936	0.612556	0.124601	0.922558	0.648985	0.896805	0.737256
0.801080	0.619461	0.933720	0.275881	0.637352	0.644996	0.713379	0.302687	0.904515	0.457172
0.101214	0.236405	0.945199	0.005975	0.893786	0.082317	0.648743	0.511871	0.298942	0.121573
0.177754	0.930066	0.390527	0.575622	0.390428	0.600575	0.460949	0.191600	0.910079	0.099444
0.846157	0.322467	0.156607	0.253388	0.739021	0.133498	0.293141	0.144834	0.626600	0.045169
0.812147	0.306383	0.201517	0.306651	0.827112	0.277716	0.660224	0.268538	0.518416	0.579216
0.691055	0.059046	0.104390	0.427038	0.148688	0.480788	0.026511	0.572705	0.745522	0.986078
0.483819	0.797573	0.174899	0.892670	0.118990	0.813221	0.857964	0.279164	0.883509	0.154562
0.165133	0.985134	0.214681	0.595309	0.741697	0.418602	0.301917	0.338913	0.680062	0.097350
0.281668	0.476899	0.839512	0.057760	0.474156	0.898409	0.482638	0.198725	0.888281	0.018872
0.554337	0.350955	0.942401	0.526759	0.509846	0.408165	0.800079	0.789263	0.564192	0.140684
0.873143	0.349662	0.238282	0.383195	0.568383	0.298471	0.490431	0.731405	0.339906	0.431645
0.401675	0.061151	0.771468	0.795760	0.365952	0.221234	0.947374	0.375686	0.828215	0.113060
0.574987	0.154831	0.808117	0.723544	0.134014	0.360957	0.166572	0.112314	0.242857	0.309290
0.745415	0.929459	0.425406	0.118845	0.386382	0.867386	0.808757	0.009573	0.229879	0.849242
0.613554	0.926550	0.857632	0.014438	0.004214	0.592513	0.280223	0.283447	0.943793	0.205750
0.880368	0.303741	0.247850	0.341580	0.867155	0.542130	0.473418	0.650251	0.326222	0.036285
0.567556	0.183534	0.696381	0.373333	0.716762	0.526636	0.306862	0.904790	0.151931	0.328792
0.280015	0.237361	0.336240	0.424191	0.192603	0.770194	0.284572	0.992475	0.308979	0.698329

Random Numbers Uniformly Distributed between Zero and One*									
0.502862	0.818555	0.238758	0.057148	0.461531	0.904929	0.521982	0.599127	0.239509	0.424858
0.738375	0.794328	0.305231	0.887161	0.021104	0.469779	0.913966	0.266514	0.647901	0.246223
0.366209	0.749763	0.634971	0.261038	0.869115	0.787951	0.678287	0.667142	0.216531	0.763214
0.739267	0.554299	0.979969	0.489597	0.545130	0.931869	0.096443	0.374089	0.140070	0.840563
0.375690	0.866922	0.256930	0.518074	0.217373	0.027043	0.801938	0.040364	0.624283	0.292810
0.894101	0.178824	0.443631	0.110614	0.556232	0.969563	0.291364	0.695764	0.306903	0.303885
0.668169	0.296926	0.324041	0.616290	0.799426	0.372555	0.070954	0.045748	0.505327	0.027722
0.470107	0.135634	0.271284	0.494071	0.485610	0.382772	0.418470	0.004082	0.298068	0.539847
0.047906	0.694949	0.309033	0.223989	0.008978	0.383695	0.479858	0.894958	0.597796	0.162072
0.917713	0.072793	0.107402	0.007328	0.176598	0.576809	0.052969	0.421803	0.737514	0.340966
0.839439	0.338565	0.254833	0.924413	0.871833	0.480599	0.172846	0.736102	0.471802	0.783451
0.488244	0.260352	0.129716	0.153558	0.305933	0.777100	0.111924	0.412930	0.601453	0.083217
0.488369	0.485094	0.322236	0.894264	0.781546	0.770237	0.707400	0.587451	0.571609	0.981580
0.311380	0.270400	0.807264	0.348433	0.172763	0.914856	0.011893	0.014317	0.820797	0.261767
0.028802	0.072165	0.944160	0.804761	0.770481	0.104256	0.112919	0.184068	0.940946	0.238087
0.466082	0.603884	0.959713	0.547834	0.487552	0.455150	0.240324	0.428921	0.648821	0.277620
0.720229	0.575779	0.939622	0.234554	0.767389	0.735335	0.941002	0.794021	0.291615	0.165732
0.861579	0.778039	0.331677	0.608231	0.646094	0.498720	0.140520	0.259197	0.782477	0.922273
0.849884	0.917789	0.816247	0.572502	0.753757	0.857324	0.988330	0.597085	0.186087	0.771997
0.989999	0.994007	0.349735	0.954437	0.741124	0.791852	0.986074	0.444554	0.177531	0.743725
0.337214	0.987184	0.344245	0.039033	0.549585	0.688526	0.225470	0.556251	0.157058	0.681447
0.706330	0.082994	0.299909	0.613361	0.031334	0.941102	0.772731	0.198070	0.460602	0.778659
0.417239	0.916556	0.707773	0.249767	0.169301	0.914420	0.732687	0.934912	0.985594	0.726957
0.653326	0.529996	0.305465	0.181747	0.153359	0.353168	0.673377	0.448970	0.546347	0.885438
0.099373	0.156385	0.067157	0.755573	0.689979	0.494021	0.996216	0.051811	0.049321	0.595525
0.860299	0.210143	0.026232	0.838499	0.108975	0.455260	0.320633	0.150619	0.445073	0.275619
0.067160	0.791992	0.363875	0.825052	0.047561	0.311194	0.447486	0.971659	0.876616	0.455018
0.944317	0.348844	0.210015	0.769274	0.253032	0.239894	0.208165	0.600014	0.945046	0.505316
0.917419	0.185575	0.743859	0.655124	0.185320	0.237660	0.271534	0.949825	0.441666	0.811135
0.365705	0.800723	0.116707	0.386073	0.837800	0.244896	0.337304	0.869528	0.845737	0.194553
0.911453	0.591254	0.920222	0.707522	0.782902	0.092884	0.426444	0.320336	0.226369	0.377845
0.027171	0.058193	0.726183	0.057705	0.935493	0.688071	0.752543	0.932781	0.048914	0.591035
0.768066	0.387888	0.655990	0.690208	0.746739	0.936409	0.685458	0.090931	0.242120	0.067899
0.052305	0.899285	0.092643	0.058916	0.826653	0.772790	0.785028	0.967761	0.588503	0.896590
0.623285	0.492051	0.644294	0.821341	0.600824	0.901289	0.774379	0.391874	0.810022	0.437879
0.624284	0.308522	0.208541	0.297156	0.576129	0.373705	0.370345	0.372748	0.965550	0.874416
0.853117	0.671602	0.018316	0.095780	0.871263	0.885420	0.919787	0.439594	0.460586	0.629443
0.967796	0.933631	0.397054	0.682343	0.505977	0.406611	0.539543	0.066152	0.885414	0.857606
0.759450	0.768853	0.115419	0.744466	0.607572	0.179839	0.413809	0.228607	0.362857	0.826932
0.514703	0.108915	0.864053	0.076280	0.352557	0.674917	0.572689	0.588574	0.596215	0.639101
0.826296	0.264540	0.255775	0.180449	0.405715	0.740170	0.423514	0.537793	0.877436	0.512284
0.354198	0.792775	0.051583	0.806962	0.385851	0.655314	0.046701	0.860466	0.848112	0.515684
0.744807	0.960789	0.123099	0.163569	0.621969	0.571558	0.482449	0.346358	0.795845	0.207558
0.642312	0.356643	0.797708	0.505570	0.418534	0.634642	0.033111	0.393330	0.105093	0.328848
0.824625	0.855876	0.770743	0.678619	0.927298	0.204828	0.831460	0.979875	0.566627	0.056160
0.755877	0.679791	0.442388	0.899944	0.563383	0.197074	0.679568	0.244433	0.786084	0.337991
0.625370	0.967123	0.321605	0.697578	0.122418	0.475395	0.068207	0.070374	0.353248	0.461960
0.124012	0.133851	0.761154	0.501578	0.204221	0.866481	0.925783	0.329001	0.327832	0.844681
0.825392	0.382001	0.847909	0.520741	0.404959	0.308849	0.418976	0.972838	0.452438	0.600528
0.999194	0.297058	0.617183	0.570478	0.875712	0.581618	0.284410	0.405575	0.362205	0.427077
0.536855	0.667083	0.636883	0.043774	0.113509	0.980045	0.237797	0.618925	0.670767	0.814902

Random Numbers Uniformly Distributed between Zero and One*									
0.361632	0.797162	0.136063	0.487575	0.682796	0.952708	0.759989	0.058556	0.292400	0.871674
0.923253	0.479871	0.022855	0.673915	0.733795	0.811955	0.417970	0.095675	0.831670	0.043950
0.845432	0.202336	0.348421	0.050704	0.171916	0.600557	0.284838	0.606715	0.758190	0.394811

* To ensure random number generation using a table, ask a disinterested party to determine the random numbers off the table.

APPENDIX J
DERIVATION OF ALPHA SCANNING EQUATIONS PRESENTED IN SECTION 6.3.2.2

For alpha survey instrumentation with a background of approximately 1 to 3 counts per minute, a single count will give a surveyor sufficient cause to stop and investigate further. Assuming this to be true, the probability of detecting given levels of alpha-emitting radionuclides can be calculated by use of Poisson summation statistics.

Experiments yielding numerical values for a random variable x, where x represents the number of events occurring during a given time interval or in a specified region in space, are often called Poisson experiments (Walpole and Myers 1985). The probability distribution of the Poisson random variable x, representing the number of events occurring in a given time interval *t*, is given by **Equation J-1**:

$$P(x;\ \lambda t) = \frac{e^{-\lambda t}(\lambda t)^x}{x!}, x = 0, 1, 2, \cdots \qquad \textbf{Equation J-1}$$

where:

$P(x;\ \lambda t)$ = probability of x events in time interval *t*
λ = average number of events per unit time
λt = average value expected

To define this distribution for an alpha scanning system, substitutions may be made, giving **Equation J-2**:

$$P(n; m) = \frac{e^{-m} m^n}{n!} \qquad \textbf{Equation J-2}$$

where:

$P(n; m)$ = probability of getting n counts when the average number expected is m
$m = \lambda t$, average number of counts expected
$n = x$, number of counts actually detected

For a given detector size, source activity, and scanning rate, the probability of getting n counts while passing over the source activity with the detector can be written as in **Equation J-3**:

$$P(n; m) = \frac{e^{\frac{-GEd}{60v}} \left[\frac{GEd}{60v}\right]^n}{n!} = \frac{e^{\frac{-GEt}{60}} \left[\frac{GEt}{60}\right]^n}{n!} \qquad \textbf{Equation J-3}$$

where:

G = source activity (disintegrations per minute [dpm])
E = detection efficiency (4π)
d = width of the detector in the direction of scan (centimeters [cm])
v = scan speed (cm/second[s])
$t = d/v$, dwell time over source(s)

If it is assumed that the detector background is equal to zero, then the probability of observing greater than or equal to 1 count, $P(n \geq 1)$ within a time interval t is as shown in **Equation J-4**:

$$P(n \geq 1) = 1 - P(n = 0) \qquad \textbf{Equation J-4}$$

If it also is assumed that a single count is sufficient to cause a surveyor to stop and investigate further, then it is as shown in **Equation J-5**:

$$P(n \geq 1) = 1 - P(n = 0) = 1 - e^{\frac{-GEt}{60}} \qquad \textbf{Equation J-5}$$

Figures J-1–J-3, at the end of this appendix, show this function plotted for three different detector sizes and three different source activity levels. Note that the source activity levels are given in terms of the concentration of residual radioactive material on the surface (dpm per 100 cm^2), the probe sizes are the dimensions of the probes in line with the direction of scanning, and the detection efficiency has been assumed to be 15 percent. The assumption is made that the residual radioactive material is contained within a 100 cm^2 area and that the detector completely passes over the area either in one or multiple passes.

Once a count has been recorded and the surveyor stops, the surveyor should[1] wait long enough so that, if the residual radioactive material corresponds to the derived concentration guideline level (DCGL), the probability of getting another count is at least 90 percent. This minimum time interval can be calculated for given DCGLs. First, calculate G based on the DCGL and detector area as shown in **Equation J-6:**

$$G = CA/100 \qquad \textbf{Equation J-6}$$

where:

C = derived concentration guideline level (dpm/cm^2)
A = detector area (cm^2)

Next, substitute G into **Equation J-5** and solve for t when $P(n \geq 1) = 0.9$**:**

$$t = \frac{13{,}800}{CAE}$$

Equation J-3 can be solved to give the probability of getting any number of counts while passing over the source area, although the solutions can become long and complex. Many portable proportional counters have background count rates on the order of 5 to 10 counts per minute, and a single count will not give a surveyor cause to stop and investigate further. If a surveyor did stop for every count and subsequently waited long enough to make sure that the previous count either was or was not caused by an elevated concentration of residual radioactive material, little or no progress would be made. For these types of instruments, the surveyor usually will need to get at least two counts while passing over the source area before

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[1] The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

stopping for further investigation. Assuming this to be a valid assumption, **Equation J-3** can be solved for $n \geq 2$ as shown:

$$P(n \geq 2) = 1 - P(n = 0) - P(n = 1)$$

$$= 1 - e^{\frac{-(GE+B)t}{60}} - \frac{(GE + B)t}{60} e^{\frac{-(GE+B)t}{60}}$$

$$= 1 - e^{\frac{-(GE+B)t}{60}} \left(1 + \frac{(GE + B)t}{60}\right)$$

where:

$P(n \geq 2) =$ probability of getting two or more counts during the time interval t
$P(n = 1) =$ probability of getting one count during the time interval t
$P(n = 0) =$ probability of not getting any counts during the time interval t
$B =$ background count rate (counts per minute)

All other variables are the same as in **Equation J-3**.

Figures J-4–J-6 show this function plotted for three different probe sizes and three different concentrations of residual radioactive material for $n \geq 2$. The same assumptions were made when calculating these curves as were made for **Figures J-1–J-3**, except that for **Figures J-1–J-3,** the background was assumed to be seven counts per minute and $n \geq 1$.

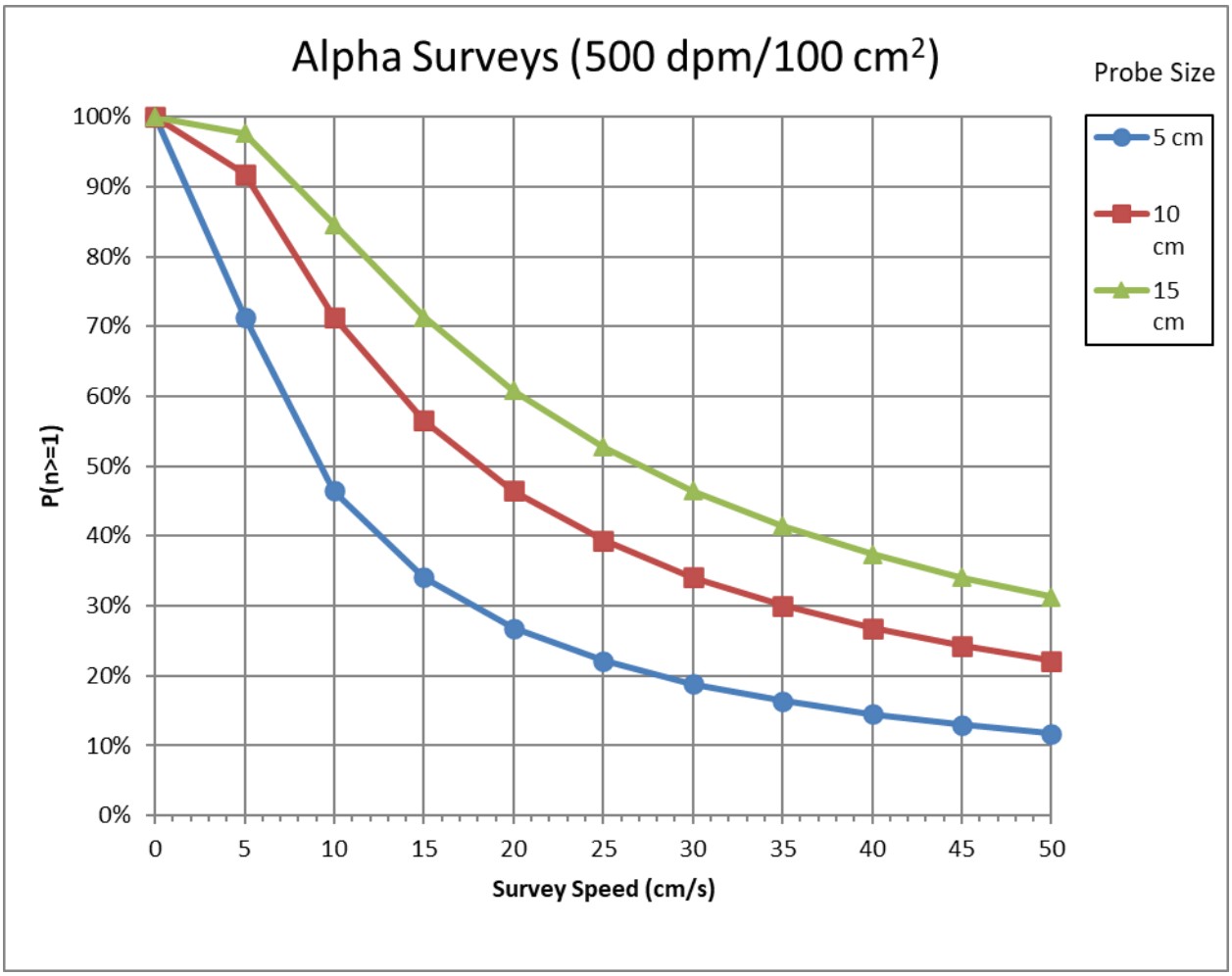

Figure J-1 Probability (P) of Getting One or More Counts When Passing Over a 100 cm² Area Containing Residual Radioactive Material at 500 dpm/100 cm² Alpha

Figure J-1 shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes, which are in line with the direction of scanning. A detection efficiency of 15 percent (4π) is assumed.

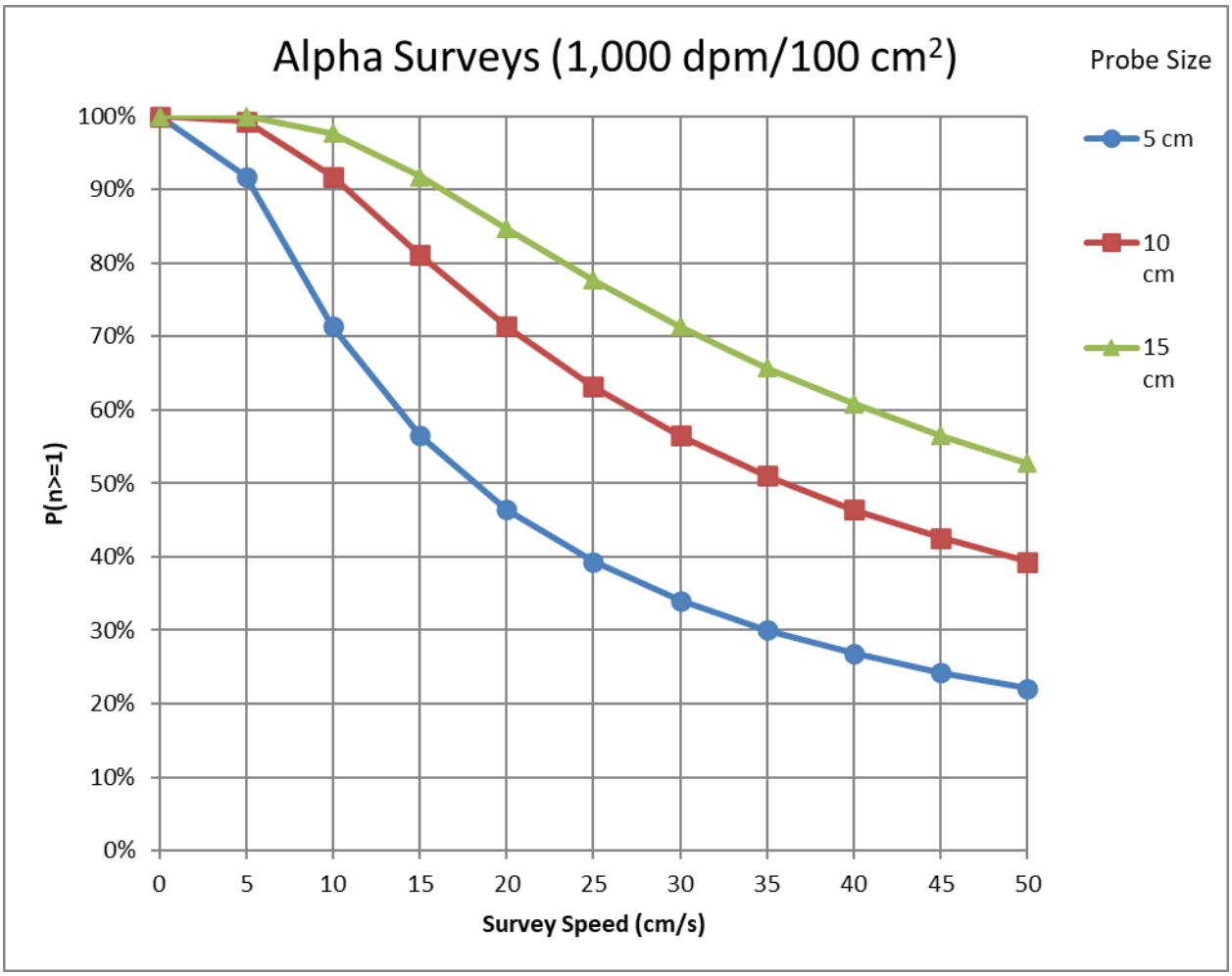

Figure J-2 Probability (P) of Getting One or More Counts When Passing Over a 100 cm² Area Containing Residual Radioactive Material at 1,000 dpm/100 cm² Alpha

Figure J-2 shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes, which are in line with the direction of scanning. A detection efficiency of 15 percent (4π) is assumed.

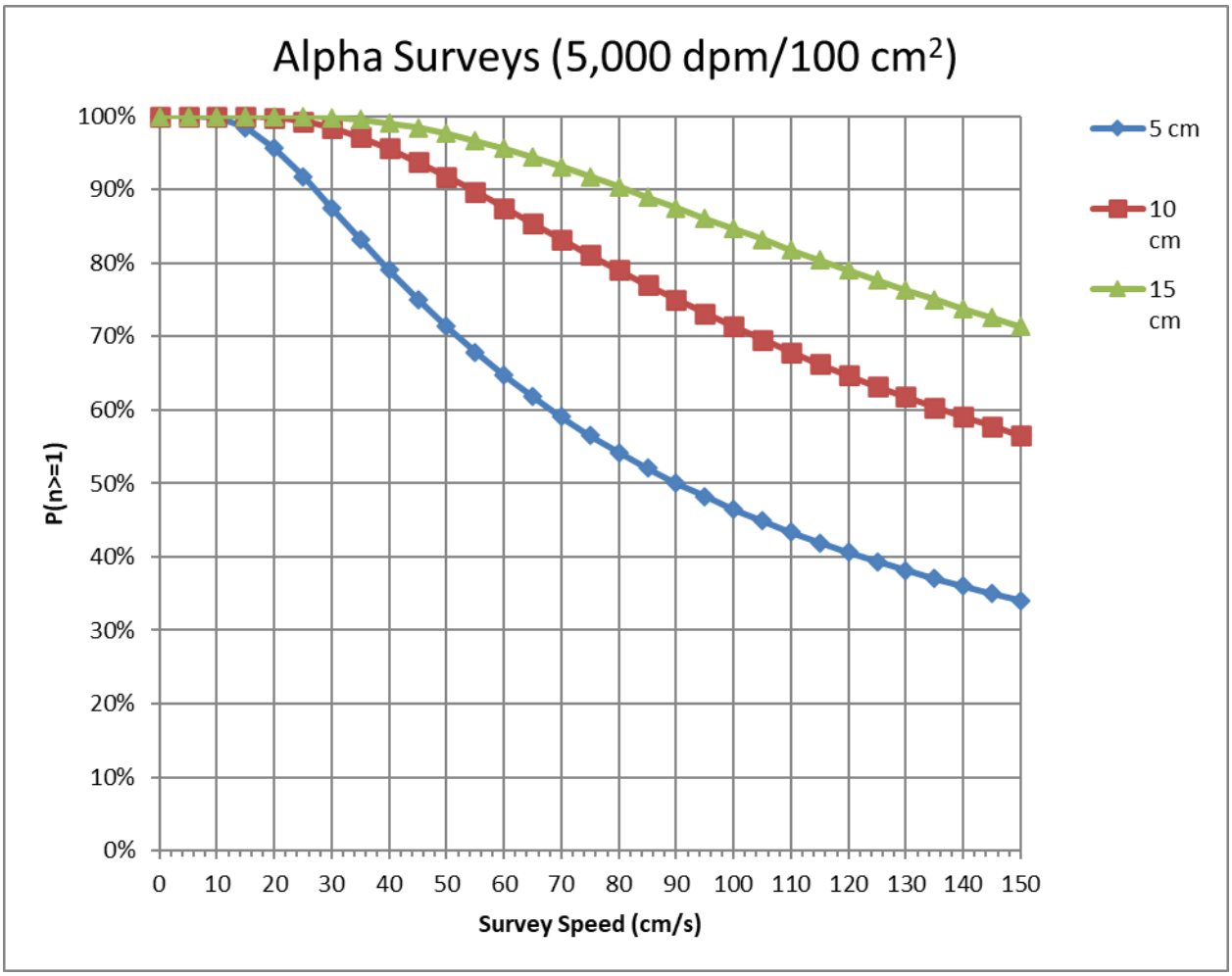

Figure J-3 Probability (P) of Getting One or More Counts When Passing Over a 100 cm² Area Containing Residual Radioactive Material at 5,000 dpm/100 cm² Alpha

Figure J-3 shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes, which are in line with the direction of scanning. A detection efficiency of 15 percent (4π) is assumed.

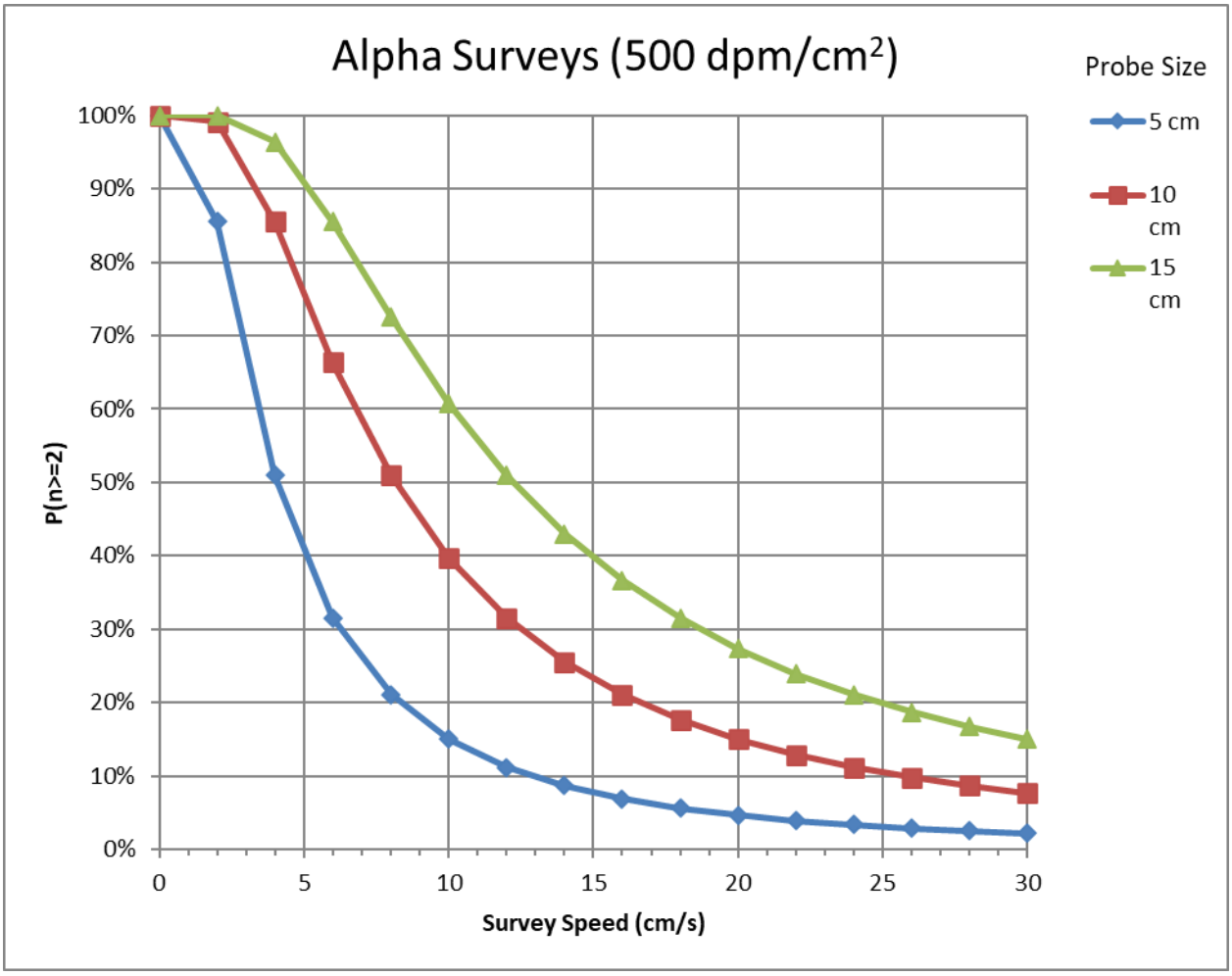

Figure J-4 Probability (*P*) of Getting Two or More Counts When Passing Over a 100 cm² Area Containing Residual Radioactive Material at 500 dpm/100 cm² Alpha

Figure J-4 shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes, which are in line with the direction of scanning. A detection efficiency of 15 percent (4π) is assumed.

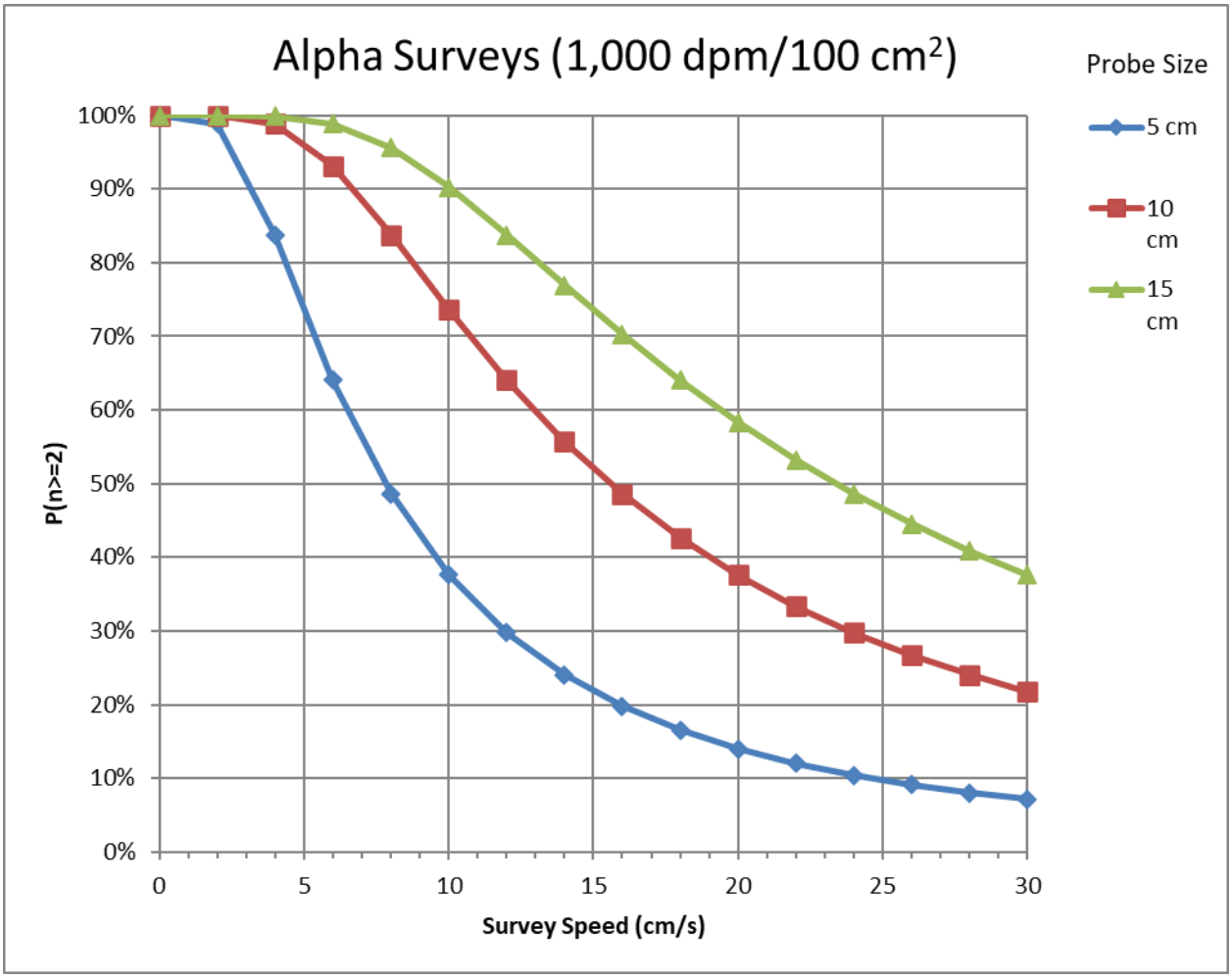

Figure J-5 Probability (*P*) of Getting Two or More Counts When Passing Over a 100 cm² Area Containing Residual Radioactive Material at 1,000 dpm/100 cm² Alpha

Figure J-5 shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes, which are in line with the direction of scanning. A detection efficiency of 15 percent (4π) is assumed.

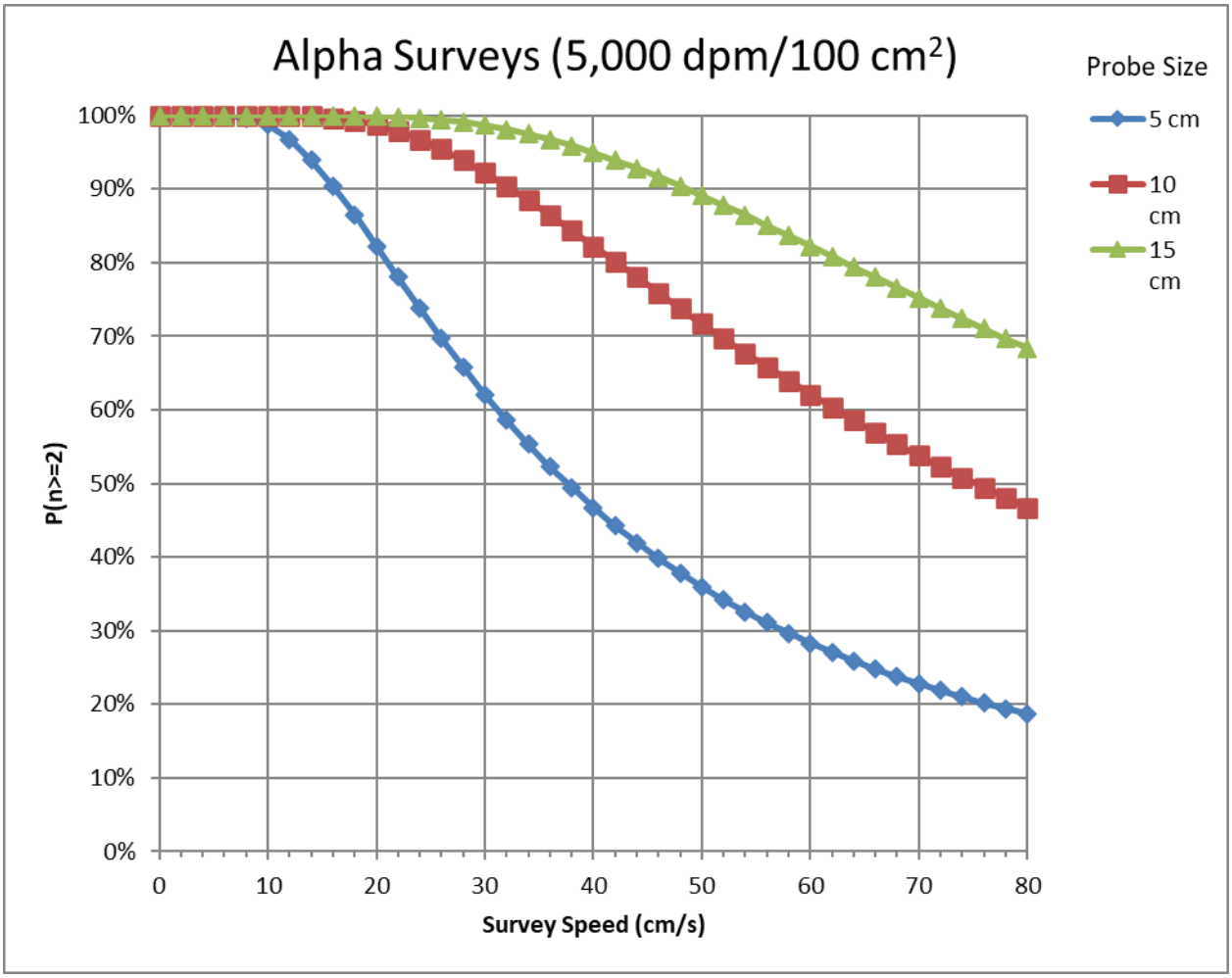

Figure J-6 Probability (*P*) of Getting Two or More Counts When Passing Over a 100 cm² Area Containing Residual Radioactive Material at 5,000 dpm/100 cm² Alpha

Figure J-6 shows the probability versus scanning speed for three different probe sizes. The probe size denotes the dimensions of the probes, which are in line with the direction of scanning. A detection efficiency of 15 percent (4π) is assumed.

APPENDIX K
UNITY RULE EXAMPLE FOR MULTIPLE RADIONUCLIDES

This appendix provides an example of the use of the unity rule where the survey unit includes multiple radionuclides at a ratio that cannot be assumed to be constant at different locations. The example illustrates the calculation of the results, the estimation of the associated standard uncertainties and the combined standard uncertainty, and the rounding and reporting of the final result to an appropriate number of digits. This example is only illustrative, and some details of the measurement method have not been included. Whenever the unity rule is used, all contributions to the combined standard uncertainty should[1] be considered and included, as appropriate.

Ten soil samples were collected during the characterization survey and analyzed by gamma spectrometry for cesium-137 (^{137}Cs) and cobalt-60 (^{60}Co). The efficiencies for ^{137}Cs and ^{60}Co are (0.135 ± 0.002) counts per second (cps) becquerel (Bq)$^{-1}$ and (0.101 ± 0.002) cps Bq^{-1}, respectively. In this example, all soil samples were counted on the same spectrometer. **Table K-1** provides the measured sample masses and net count rates, along with their associated standard (1σ) uncertainties. The derived concentration guideline level for average concentrations over a wide area ($DCGL_W$) for ^{137}Cs is 350 Bq per kilogram (kg^{-1}), and for ^{60}Co, the $DCGL_W$ is 90 Bq kg^{-1}.

Table K-1 Measured Sample Masses and Net Count Rates

Sample	Mass of Sample (kg)	Net Count Rate (cps) ^{137}Cs	Net Count Rate (cps) ^{60}Co
1	0.500 ± 0.005	11.60 ± 1.28	3.83 ± 0.86
2	0.493 ± 0.005	8.93 ± 1.29	4.00 ± 0.84
3	0.496 ± 0.005	12.27 ± 1.34	1.77 ± 0.87
4	0.494 ± 0.005	7.50 ± 1.28	1.53 ± 0.85
5	0.502 ± 0.005	12.03 ± 1.31	2.03 ± 0.86
6	0.502 ± 0.005	5.83 ± 1.23	3.03 ± 0.86
7	0.498 ± 0.005	6.07 ± 1.25	1.70 ± 0.83
8	0.490 ± 0.005	11.00 ± 1.26	3.23 ± 0.88
9	0.502 ± 0.005	13.57 ± 1.35	3.90 ± 0.88
10	0.513 ± 0.005	4.23 ± 1.23	1.60 ± 0.86

This example includes the following four tasks:

(1) Task 1 is to determine the activity concentrations of ^{137}Cs and ^{60}Co and their associated uncertainties in the individual soil samples.

(2) Task 2 is to determine the sum of fractions and the associated uncertainties for the individual soil samples.

[1] The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

(3) Task 3 is to determine the average (i.e., mean) activity concentrations of ^{137}Cs and ^{60}Co and their associated uncertainties in the 10 soil samples.

(4) Task 4 is to determine the average (i.e., mean) sum of fractions and the associated uncertainty for the 10 soil samples.

Task 1: Determine the Activity Concentrations of ^{137}Cs and ^{60}Co in Individual Soil Samples

Step 1 is to identify the measurand and all the input quantities for the mathematical measurement model. The measurand is the activity concentrations of ^{137}Cs or ^{60}Co in the individual soil samples. The input quantities are the net count rate, spectrometer efficiency, and sample mass.

Step 2 is to estimate the value of each input quantity. The spectrometer efficiencies are given as 0.135 cps Bq^{-1} and 0.101 cps Bq^{-1} for ^{137}Cs and ^{60}Co, respectively. **Table K-1** provides estimates for the values of net count rate and sample mass.

Step 3 is to evaluate the standard uncertainty for each input estimate using either a Type A or Type B method of evaluation. The standard uncertainties in spectrometer efficiencies are given as 0.002 cps Bq^{-1} and 0.002 cps Bq^{-1} for ^{137}Cs and ^{60}Co, respectively. **Table K-1** shows the standard uncertainties for net count rates and sample masses.

Step 4 is to evaluate the covariances for all pairs of input estimates with potentially significant correlations. The input variables are independent, and there are no correlations between any pairs of input estimates.

Step 5 is to estimate the measurand from the mathematical measurement model determined in Step 1. For each sample, the activity concentrations of ^{137}Cs and ^{60}Co were calculated along with their standard uncertainty. The activity concentrations of ^{137}Cs, $C_{Cs,i}$, and ^{60}Co, $C_{Co,i}$, in the ith soil sample are as follows:

$$C_{Cs,i} = \frac{R_{Cs,i}}{\varepsilon_{Cs} \cdot m_i} \qquad \textbf{Equation K-1}$$

$$C_{Co,i} = \frac{R_{Co,i}}{\varepsilon_{Co} \cdot m_i} \qquad \textbf{Equation K-2}$$

where:

ε_{Cs} = detector efficiency for ^{137}Cs (cps Bq^{-1})
$R_{Cs,i}$ = net count rate for ^{137}Cs for the ith soil sample (cps)
ε_{Co} = detector efficiency for ^{60}Co (cps Bq^{-1})
$R_{Co,i}$ = net count rate for ^{60}Co for the ith soil sample (cps)
m_i = mass of the ith soil sample (kg)

For example, for the first sample, the activity concentration of ^{137}Cs is as follows:

$$C_{\mathrm{Cs},i} = \frac{R_{\mathrm{Cs},i}}{\varepsilon_{\mathrm{Cs}} \cdot m_i}$$
$$= \frac{11.60 \text{ cps}}{(0.135 \text{ cps Bq}^{-1})(0.500 \text{ kg})}$$
$$= 172 \text{ Bq kg}^{-1}$$

The activity concentration of ^{60}Co for the first sample is as follows:

$$C_{\mathrm{Co},1} = \frac{R_{\mathrm{Co},i}}{\varepsilon_{\mathrm{Co}} \cdot m_i}$$
$$= \frac{3.83 \text{ cps}}{(0.101 \text{ cps Bq}^{-1})(0.500 \text{ kg})}$$
$$= 76 \text{ Bq kg}^{-1}$$

Step 6 is to determine the combined standard uncertainty of the estimate of the measurand. The absolute uncertainty in activity concentrations of ^{137}Cs, $u_c(C_{\mathrm{Cs},i})$, and ^{60}Co, $u_c(C_{\mathrm{Co},i})$, in the ith soil sample are given by the following:

$$u_c^2(C_{\mathrm{Cs},i}) = \left(\frac{\partial C_{\mathrm{Cs},i}}{\partial m_i}\right)^2 u^2(m_i) + \left(\frac{\partial C_{\mathrm{Cs},i}}{\partial \varepsilon_{\mathrm{Cs}}}\right)^2 u^2(\varepsilon_{\mathrm{Cs}}) + \left(\frac{\partial C_{\mathrm{Cs},i}}{\partial R_{\mathrm{Cs},i}}\right)^2 u^2(R_{\mathrm{Cs},i}) \quad \textbf{Equation K-3}$$

$$u_c^2(C_{\mathrm{Co},i}) = \left(\frac{\partial C_{\mathrm{Co},i}}{\partial m_i}\right)^2 u^2(m_i) + \left(\frac{\partial C_{\mathrm{Co},i}}{\partial \varepsilon_{\mathrm{Cs}}}\right)^2 u^2(\varepsilon_{\mathrm{Co}}) + \left(\frac{\partial C_{\mathrm{Co},i}}{\partial R_{\mathrm{Co},i}}\right)^2 u^2(R_{\mathrm{Co},i}) \quad \textbf{Equation K-4}$$

where:

$u(\varepsilon_{\mathrm{Cs}})$ = absolute uncertainty in the detector efficiency for ^{137}Cs (cps Bq^{-1})

$u(R_{\mathrm{Cs},i})$ = absolute uncertainty in the net count rate for ^{137}Cs for the ith soil sample (cps)

$u(\varepsilon_{\mathrm{Co}})$ = absolute uncertainty in the detector efficiency for ^{60}Co (cps Bq^{-1})

$u(R_{\mathrm{Co},i})$ = absolute uncertainty in the net count rate for ^{60}Co for the ith soil sample (cps)

$u(m_i)$ = absolute uncertainty in the mass of the ith soil sample (kg)

Evaluating the partial derivatives—

$$\frac{\partial C_{\mathrm{Cs},i}}{\partial m_i} = \frac{-R_{\mathrm{Cs},i}}{{m_i}^2 \cdot \varepsilon_{\mathrm{Cs}}} \qquad \frac{\partial C_{\mathrm{Co},i}}{\partial m_i} = \frac{-R_{\mathrm{Co},i}}{{m_i}^2 \cdot \varepsilon_{\mathrm{Cs}}}$$

$$\frac{\partial C_{\mathrm{Cs},i}}{\partial \varepsilon_{\mathrm{Cs}}} = \frac{-R_{\mathrm{Cs},i}}{m_i \cdot {\varepsilon_{\mathrm{Cs}}}^2} \qquad \frac{\partial C_{\mathrm{Co},i}}{\partial \varepsilon_{\mathrm{Cs}}} = \frac{-R_{\mathrm{Co},i}}{m_i \cdot {\varepsilon_{\mathrm{Cs}}}^2}$$

$$\frac{\partial C_{\mathrm{Cs},i}}{\partial R_{\mathrm{Cs},i}} = \frac{1}{m_i \cdot \varepsilon_{\mathrm{Cs}}} \qquad \frac{\partial C_{\mathrm{Co},i}}{\partial R_{\mathrm{Cs},i}} = \frac{1}{m_i \cdot \varepsilon_{\mathrm{Co}}}$$

Substituting the partial derivatives into **Equation K-3** and **Equation K-4** and simplifying, the standard uncertainties in activity concentrations of ^{137}Cs, $u_c(C_{\mathrm{Cs},i})$, and ^{60}Co, $u_c(C_{\mathrm{Co},i})$, in the ith soil sample are given by the following:

$$u_c^2(C_{\mathrm{Cs},i}) = {C_{\mathrm{Cs},i}}^2 \left[\frac{u^2(\varepsilon_{\mathrm{Cs}})}{{\varepsilon_{\mathrm{Cs}}}^2} + \frac{u^2(R_{\mathrm{Cs},i})}{{R_{\mathrm{Cs},i}}^2} + \frac{u^2(m_i)}{{m_i}^2}\right] \qquad \textbf{Equation K-5}$$

$$u_c^2(C_{\mathrm{Co},i}) = {C_{\mathrm{Co},i}}^2 \left[\frac{u^2(\varepsilon_{\mathrm{Co}})}{{\varepsilon_{\mathrm{Co}}}^2} + \frac{u^2(R_{\mathrm{Co},i})}{{R_{\mathrm{Co},i}}^2} + \frac{u^2(m_i)}{{m_i}^2}\right] \qquad \textbf{Equation K-6}$$

Taking the square root of both sides of **Equation K-5** and **Equation K-6**, the absolute uncertainties in activity concentrations of ^{137}Cs, $u_c(C_{\mathrm{Cs},i})$, and ^{60}Co, $u_c(C_{\mathrm{Co},i})$, in the ith soil sample are as follows:

$$u_c(C_{\mathrm{Cs},i}) = |C_{\mathrm{Cs},i}| \sqrt{\frac{u^2(\varepsilon_{\mathrm{Cs}})}{{\varepsilon_{\mathrm{Cs}}}^2} + \frac{u^2(R_{\mathrm{Cs},i})}{{R_{\mathrm{Cs},i}}^2} + \frac{u^2(m_i)}{{m_i}^2}} \qquad \textbf{Equation K-7}$$

$$u_c(C_{\mathrm{Co},i}) = |C_{\mathrm{Co},i}| \sqrt{\frac{u^2(\varepsilon_{\mathrm{Co}})}{{\varepsilon_{\mathrm{Co}}}^2} + \frac{u^2(R_{\mathrm{Co},i})}{{R_{\mathrm{Co},i}}^2} + \frac{u^2(m_i)}{{m_i}^2}} \qquad \textbf{Equation K-8}$$

where:

$u(\varepsilon_{\mathrm{Cs}})$ = standard uncertainty in the detector efficiency for ^{137}Cs (cps Bq^{-1})

$\varepsilon_{\mathrm{Cs}}$ = detector efficiency for ^{137}Cs (cps Bq^{-1})

$u(R_{\mathrm{Cs},i})$ = standard uncertainty in the net count rate for ^{137}Cs for the ith soil sample (cps)

$R_{\mathrm{Cs},i}$ = net count rate for ^{137}Cs for the ith soil sample (cps)

$u(\varepsilon_{\mathrm{Co}})$ = standard uncertainty in the detector efficiency for ^{60}Co (cps Bq^{-1})

$\varepsilon_{\mathrm{Co}}$ = detector efficiency for ^{60}Co (cps Bq^{-1})

$u(R_{\mathrm{Co},i})$ = standard uncertainty in the net count rate for ^{60}Co for the ith soil sample (cps)

$R_{\mathrm{Co},i}$ = net count rate for ^{60}Co for the ith soil sample (cps)

$u(m_i)$ = standard uncertainty in the mass of the ith soil sample (kg)

m_i = mass of the ith soil sample (kg)

For example, the standard uncertainty for the activity concentration of ^{137}Cs for the first sample is as follows:

$$u_c(C_{\mathrm{Cs},i}) = |C_{\mathrm{Cs},i}|\sqrt{\frac{u^2(\varepsilon_{\mathrm{Cs}})}{{\varepsilon_{\mathrm{Cs}}}^2} + \frac{u^2(R_{\mathrm{Cs},i})}{{R_{\mathrm{Cs},i}}^2} + \frac{u^2(m_i)}{{m_i}^2}}$$

$$= (172 \text{ Bq kg}^{-1})\sqrt{\left(\frac{0.002 \text{ cps Bq}^{-1}}{0.135 \text{ cps Bq}^{-1}}\right)^2 + \left(\frac{1.28 \text{ cps}}{11.60 \text{ cps}}\right)^2 + \left(\frac{0.005 \text{ kg}}{0.500 \text{ kg}}\right)^2}$$

$$= 19 \text{ Bq kg}^{-1}$$

The standard uncertainty for the activity concentration of ^{60}Co for the first sample is as follows:

$$u_c(C_{\mathrm{Co},i}) = |C_{\mathrm{Co},i}|\sqrt{\frac{u^2(\varepsilon_{\mathrm{Co}})}{{\varepsilon_{\mathrm{Co}}}^2} + \frac{u^2(R_{\mathrm{Co},i})}{{R_{\mathrm{Co},i}}^2} + \frac{u^2(m_i)}{{m_i}^2}}$$

$$= (76 \text{ Bq kg}^{-1})\sqrt{\left(\frac{0.002 \text{ cps Bq}^{-1}}{0.101 \text{ cps Bq}^{-1}}\right)^2 + \left(\frac{0.86 \text{ cps}}{3.83 \text{ cps}}\right)^2 + \left(\frac{0.005 \text{ kg}}{0.500 \text{ kg}}\right)^2}$$

$$= 17 \text{ Bq kg}^{-1}$$

Table K-2 shows the activity concentrations and their associated uncertainties for individual samples.

Table K-2 Activity Concentrations for Soil Samples

Sample	Activity Concentration (Bq kg^{-1}) ^{137}Cs	Activity Concentration (Bq kg^{-1}) ^{60}Co
1	172 ± 19	76 ± 17
2	134 ± 19	80 ± 17
3	183 ± 20	35 ± 17
4	112 ± 19	31 ± 17
5	178 ± 20	40 ± 17
6	86 ± 18	60 ± 17

Sample	Activity Concentration (Bq kg^{-1}) ^{137}Cs	Activity Concentration (Bq kg^{-1}) ^{60}Co
7	90 ± 19	34 ± 17
8	166 ± 19	65 ± 18
9	200 ± 20	77 ± 17
10	61 ± 18	31 ± 17

Step 7 is to optionally[2] multiply the combined standard uncertainty of the estimate of the measurand by a coverage factor, k, to obtain the expanded uncertainty to construct an interval that can be expected to contain the true value of the measurand with a specified (high) probability. The reported standard uncertainty or expanded uncertainty should usually be rounded to two significant figures and the estimate of the measurand rounded to the same number of digits. The values calculated before rounding should be used in any subsequent calculations to avoid rounding errors.

Step 8 is to report the result as the estimate of the measurand ± the expanded uncertainty, together with the unit of measurement and, at a minimum, to state the coverage factor used to compute the expanded uncertainty and the estimated coverage probability. The estimated activity concentration can be reported as follows:

$$C_{\mathrm{Cs},i} \pm k \cdot u_C(C_{\mathrm{Cs},i}) \qquad \textbf{Equation K-9}$$

$$C_{\mathrm{Co},i} \pm k \cdot u_C(C_{\mathrm{Co},i}) \qquad \textbf{Equation K-10}$$

where *k* is a coverage factor to obtain the expanded uncertainty, such that the interval $[C_{\mathrm{Cs},i} - k \cdot u_C(C_{\mathrm{Cs},i}),\ C_{\mathrm{Cs},i} + k \cdot u_C(C_{\mathrm{Cs},i})]$ or $[C_{\mathrm{Co},i} - k \cdot u_C(C_{\mathrm{Co},i}),\ C_{\mathrm{Co},i} + k \cdot u_C(C_{\mathrm{Co},i})]$ can be expected to contain the value of the measurand with a specified (high) probability.

Using a coverage factor of 2 and an estimated coverage probability of 95 percent, the estimated activity concentration of ^{137}Cs in the first sample is (172 ± 38) Bq kg^{-1}. The activity concentration of ^{60}Co in the first sample is (76 ± 34) Bq kg^{-1}, again using a coverage factor of 2 and an estimated coverage probability of 95 percent.

Task 2: Determine the Sum of Fractions and the Associated Standard Uncertainty for Individual Soil Samples

Step 1 is to identify the measurand and all the input quantities for the mathematical measurement model. The measurand is the sum of fractions for the individual soil samples. The input quantities are the net count rates, spectrometer efficiencies, sample masses, and DCGLs.

[2] Completing this step allows the user to determine a confidence interval that can be expected to contain the true value of the measurand with a specified probability. For normal distributions, a coverage factor of 2 correlates to a confidence interval of approximately 95 percent. **Section 6.4.3.7** provides more information.

Step 2 is to estimate the value of each input quantity. The spectrometer efficiencies are given as 0.135 cps Bq^{-1} and 0.101 cps Bq^{-1} for ^{137}Cs and ^{60}Co, respectively. The DCGLs are given as 350 Bq kg^{-1} and 90 Bq kg^{-1} for ^{137}Cs and ^{60}Co, respectively. **Table K-1** provides estimates for the values of the net count rates and sample masses.

Step 3 is to evaluate the standard uncertainty for each input estimate using either a Type A or Type B method of evaluation. The standard uncertainties in spectrometer efficiencies are given as 0.002 cps Bq^{-1} and 0.002 cps Bq^{-1} for ^{137}Cs and ^{60}Co, respectively. The DCGLs are assumed to be free of uncertainty. **Table K-1** shows the standard uncertainties for net count rates and sample masses.

Step 4 is to evaluate the covariances for all pairs of input estimates with potentially significant correlations. The input variables are independent, and there are no correlations between any pairs of input estimates.

Step 5 is to estimate the measurand from the mathematical measurement model determined in Step 1. The sum of fractions for the ith soil sample, T_i, is as follows:

$$T_i = \frac{C_{\mathrm{Cs},i}}{\mathrm{DCGL_{Cs}}} + \frac{C_{\mathrm{Co},i}}{\mathrm{DCGL_{Co}}} = \frac{1}{m_i}\left[\frac{R_{\mathrm{Cs},i}}{\varepsilon_{\mathrm{Cs}} \cdot \mathrm{DCGL_{Cs}}} + \frac{R_{\mathrm{Co},i}}{\varepsilon_{\mathrm{Co}} \cdot \mathrm{DCGL_{Co}}}\right] \qquad \textbf{Equation K-11}$$

where:

$C_{\mathrm{Cs},i}$ = activity concentration of ^{137}Cs in the ith soil sample (Bq kg^{-1})
$\mathrm{DCGL_{Cs}}$ = DCGL for ^{137}Cs(Bq kg^{-1})
$R_{\mathrm{Cs},i}$ = net count rate for ^{137}Cs for the ith soil sample (cps)
$\varepsilon_{\mathrm{Cs}}$ = detector efficiency for ^{137}Cs (cps Bq^{-1})
$C_{\mathrm{Co},i}$ = activity concentration of ^{60}Co in the ith soil sample (Bq kg^{-1})
$\mathrm{DCGL_{Co}}$ = DCGL for ^{60}Co (Bq kg^{-1})
$R_{\mathrm{Co},i}$ = net count rate for ^{60}Co for the ith soil sample (cps)
$\varepsilon_{\mathrm{Co}}$ = detector efficiency for ^{60}Co (cps Bq^{-1})
m_i = mass of the ith sample (kg)

For example, for the first sample—

$$T_1 = \frac{C_{\mathrm{Cs},1}}{\mathrm{DCGL_{Cs}}} + \frac{C_{\mathrm{Co},1}}{\mathrm{DCGL_{Co}}}$$

$$= \frac{172 \text{ Bq kg}^{-1}}{350 \text{ Bq kg}^{-1}} + \frac{76 \text{ Bq kg}^{-1}}{90 \text{ Bq kg}^{-1}}$$

$$= 1.334$$

provides the sum of fractions for individual samples.

Table K-3 Activity Concentrations and Sum of Fractions for Soil Samples

Sample	Activity Concentration (Bq kg^{-1}) ^{137}Cs	Activity Concentration (Bq kg^{-1}) ^{60}Co	Sum of Fraction
1	172 ± 19	76 ± 17	1.33 ± 0.20
2	134 ± 19	80 ± 17	1.28 ± 0.20
3	183 ± 20	35 ± 17	0.92 ± 0.20
4	112 ± 19	31 ± 17	0.66 ± 0.20
5	178 ± 20	40 ± 17	0.95 ± 0.20
6	86 ± 18	60 ± 17	0.91 ± 0.20
7	90 ± 19	34 ± 17	0.63 ± 0.19
8	166 ± 19	65 ± 18	1.20 ± 0.21
9	200 ± 20	77 ± 17	1.43 ± 0.20
10	61 ± 18	31 ± 17	0.52 ± 0.19
Average	138.3 ± 6.4	52.9 ± 5.5	0.983 ± 0.064

Step 6 is to determine the combined standard uncertainty of the estimate of the measurand. The standard uncertainty in sum of fractions in the ith soil sample, $u_c(T_i)$, is given by **Equation K-12**:

$$u_c^2(T_i) = \left(\frac{\partial T_i}{\partial m_i}\right)^2 u^2(m_i) + \left(\frac{\partial T_i}{\partial \varepsilon_{Cs}}\right)^2 u^2(\varepsilon_{Cs}) + \left(\frac{\partial T_i}{\partial R_{Cs,i}}\right)^2 u^2(R_{Cs,i}) + \left(\frac{\partial T_i}{\partial \varepsilon_{Co}}\right)^2 u^2(\varepsilon_{Co}) + \left(\frac{\partial T_i}{\partial R_{Co,i}}\right)^2 u^2(R_{Co,i}) \quad \textbf{Equation K-12}$$

where:

$u(m_i)$ = standard uncertainty in the mass of the ith sample (kg)

$u(\varepsilon_{Cs})$ = standard uncertainty in the detector efficiency for ^{137}Cs (cps Bq^{-1})

$u(R_{Cs,i})$ = standard uncertainty in the net count rate for ^{137}Cs for the ith soil sample (cps)

$u(\varepsilon_{Co})$ = standard uncertainty in the detector efficiency for ^{60}Co (cps Bq^{-1})

$u(R_{Co,i})$ = standard uncertainty in the net count rate for ^{60}Co for the ith soil sample (cps)

Evaluating the partial derivatives—

$$\frac{\partial T_i}{\partial m_i} = \frac{-1}{{m_i}^2}\left[\frac{R_{\mathrm{Cs},i}}{\varepsilon_{\mathrm{Cs}} \cdot \mathrm{DCGL_{Cs}}} + \frac{\varepsilon_{\mathrm{Co}} \cdot R_{\mathrm{Co},i}}{\varepsilon_{\mathrm{Co}} \cdot \mathrm{DCGL_{Co}}}\right] \qquad \frac{\partial T_i}{\partial \varepsilon_{\mathrm{Co}}} = \frac{-R_{\mathrm{C0},i}}{m_i \cdot {\varepsilon_{\mathrm{Co}}}^2 \cdot \mathrm{DCGL_{Co}}}$$

$$\frac{\partial T_i}{\partial \varepsilon_{\mathrm{Cs}}} = \frac{-R_{\mathrm{Cs},i}}{m_i \cdot {\varepsilon_{\mathrm{Cs}}}^2 \cdot \mathrm{DCGL_{Cs}}} \qquad \frac{\partial T_i}{\partial R_{\mathrm{Co},i}} = \frac{1}{m_i \cdot \varepsilon_{\mathrm{Co}} \cdot \mathrm{DCGL_{Co}}}$$

$$\frac{\partial T_i}{\partial R_{\mathrm{Cs},i}} = \frac{1}{m_i \cdot \varepsilon_{\mathrm{Cs}} \cdot \mathrm{DCGL_{Cs}}}$$

Substituting the partial derivatives into **Equation K-12** and simplifying, the standard uncertainty for the sum of fractions for the ith soil sample, $u_c(T_i)$, is given by the following:

$$u_c^2(T_i) = \left(\frac{C_{\mathrm{Cs},i}}{\mathrm{DCGL_{Cs}}}\right)^2 \left[\frac{u^2(R_{\mathrm{Cs},i})}{{R_{\mathrm{Cs},i}}^2} + \frac{u^2(\varepsilon_{\mathrm{Cs}})}{{\varepsilon_{\mathrm{Cs}}}^2}\right] + \left(\frac{C_{\mathrm{Co},i}}{\mathrm{DCGL_{Co}}}\right)^2 \left[\frac{u^2(R_{\mathrm{Co},i})}{{R_{\mathrm{Co},i}}^2} + \frac{u^2(\varepsilon_{\mathrm{Co}})}{{\varepsilon_{\mathrm{Co}}}^2}\right] + {T_i}^2 \left[\frac{u^2(m_i)}{{m_i}^2}\right] \qquad \textbf{Equation K-13}$$

Taking the square root of both sides of **Equation K-13**, the absolute uncertainty for the sum of fractions for the ith soil sample, $u_c(T_i)$, is as follows:

$$u_c(T_i) = \left\{\left(\frac{C_{\mathrm{Cs},i}}{\mathrm{DCGL_{Cs}}}\right)^2 \left[\frac{u^2(R_{\mathrm{Cs},i})}{{R_{\mathrm{Cs},i}}^2} + \frac{u^2(\varepsilon_{\mathrm{Cs}})}{{\varepsilon_{\mathrm{Cs}}}^2}\right] + \left(\frac{C_{\mathrm{Co},i}}{\mathrm{DCGL_{Co}}}\right)^2 \left[\frac{u^2(R_{\mathrm{Co},i})}{{R_{\mathrm{Co},i}}^2} + \frac{u^2(\varepsilon_{\mathrm{Co}})}{{\varepsilon_{\mathrm{Co}}}^2}\right] + {T_i}^2 \left[\frac{u^2(m_i)}{{m_i}^2}\right]\right\}^{½} \qquad \textbf{Equation K-14}$$

where:

$C_{\mathrm{Cs},I}$ = activity concentration of ^{137}Cs in the ith soil sample (Bq kg^{-1})

$\mathrm{DCGL_{Cs}}$ = $\mathrm{DCGL_W}$ for ^{137}Cs (Bq kg^{-1})

$u(R_{\mathrm{Cs},i})$ = standard uncertainty in the net count rate for ^{137}Cs for the ith soil sample (cps)

$R_{\mathrm{Cs},i}$ = net count rate for ^{137}Cs for the ith soil sample (cps)

$u(\varepsilon_{\mathrm{Cs}})$ = standard uncertainty in the detector efficiency for ^{137}Cs (cps Bq^{-1})

$\varepsilon_{\mathrm{Cs}}$ = detector efficiency for ^{137}Cs (cps Bq^{-1})

$C_{\mathrm{Co},i}$ = activity concentration of ^{60}Co in the ith soil sample (Bq kg^{-1})

$\mathrm{DCGL_{Co}}$ = DCGL for ^{60}Co (Bq kg^{-1})

$u(R_{\mathrm{Co},i})$ = standard uncertainty in the net count rate for ^{60}Co for the ith soil sample (cps)

$R_{\mathrm{Co},i}$ = net count rate for ^{60}Co for the ith soil sample (cps)

$u(\varepsilon_{\mathrm{Co}})$ = standard uncertainty in the detector efficiency for ^{60}Co (cps Bq^{-1})

$\varepsilon_{\mathrm{Co}}$ = detector efficiency for ^{60}Co (cps Bq^{-1})

$u(m_i)$ = standard uncertainty in the mass of the ith sample (kg)

m_i = mass of the ith sample (kg)

For example, the standard uncertainty in the sum of fractions for the first sample is as follows:

$$u_c(T_i) = \{(\frac{C_{Cs,i}}{DCGL_{Cs}})^2 [\frac{u^2(R_{Cs,i})}{R_{Cs,i}^2} + \frac{u^2(\varepsilon_{Cs})}{\varepsilon_{Cs}^2}] + (\frac{C_{Co,i}}{DCGL_{Co}})^2 [\frac{u^2(R_{Co,i})}{R_{Co,i}^2} + \frac{u^2(\varepsilon_{Co})}{\varepsilon_{Co}^2}] + T_i^2 [\frac{u^2(m_i)}{m_i^2}]\}^{½}$$

$$= \{(\frac{172 \text{ Bq kg}^{-1}}{350 \text{ Bq kg}^{-1}})^2 [(\frac{1.28 \text{ cps}}{11.60 \text{ cps}})^2 + (\frac{0.002 \text{ cps Bq}^{-1}}{0.135 \text{ cps Bq}^{-1}})^2]$$

$$+ (\frac{76 \text{ Bq kg}^{-1}}{90 \text{ Bq kg}^{-1}})^2 [(\frac{0.86 \text{ cps}}{3.83 \text{ cps}})^2 + (\frac{0.002 \text{ cps Bq}^{-1}}{0.101 \text{ cps Bq}^{-1}})^2] + (1.334)^2 (\frac{0.005 \text{ kg}}{0.500 \text{ kg}})^2\}^{½}$$

$$= 0.20$$

Table K-3 provides the uncertainties in the sum of fractions for individual samples.

Step 7 is to optionally multiply the combined standard uncertainty of the estimate of the measurand by a coverage factor, k, to obtain the expanded uncertainty to construct an interval that can be expected to contain the true value of the measurand with a specified (high) probability. The reported standard uncertainty or expanded uncertainty should usually be rounded to two significant figures and the estimate of the measurand rounded to the same number of digits. The values calculated before rounding should be used in any subsequent calculations to avoid rounding errors.

Step 8 is to report the result as the estimate of the measurand ± the expanded uncertainty, together with the unit of measurement, and, at a minimum, to state the coverage factor used to compute the expanded uncertainty and the estimated coverage probability.

The estimated activity concentration can be reported as follows:

$$T_i \pm k \cdot u_C(T_i) \qquad \textbf{Equation K-15}$$

where *k* is a coverage factor to obtain the expanded uncertainty, such that the interval $[T_i - k \cdot u_C(T_i),\ T_i + k \cdot u_C(T_i)]$ can be expected to contain the value of the measurand with a specified (high) probability.

Using a coverage factor of 2 and an estimated coverage probability of 95 percent, the estimated sum of fractions for the first sample is 1.33 ± 0.40.

Task 3: Average Activity Concentrations and Associated Standard Uncertainties of ^{137}Cs and ^{60}Co in Soil Samples

Step 1 is to identify the measurand and all the input quantities for the mathematical measurement model. The measurand is the average activity concentrations of ^{137}Cs or ^{60}Co in the 10 soil samples. The input quantities are the net count rates, spectrometer efficiency, and sample masses.

Step 2 is to estimate the value of each input quantity. The spectrometer efficiencies are given as 0.135 cps Bq^{-1} and 0.101 cps Bq^{-1} for ^{137}Cs and ^{60}Co, respectively. **Table K-1** shows estimates for the values of net count rate and sample mass.

Step 3 is to evaluate the standard uncertainty for each input estimate using either a Type A or Type B method of evaluation. The standard uncertainties in spectrometer efficiencies are given as 0.002 cps Bq^{-1} and 0.002 cps Bq^{-1} for ^{137}Cs and ^{60}Co, respectively. **Table K-1** provides the standard uncertainties for net count rates and sample masses.

Step 4 is to evaluate the covariances for all pairs of input estimates with potentially significant correlations. The input variables are independent, and there are no correlations between any pairs of input estimates.

Step 5 is to estimate the measurand from the mathematical measurement model determined in Step 1. The average activity concentrations of ^{137}Cs, $\bar{C}_{Cs}$, and ^{60}Co, $\bar{C}_{Co}$, in the *N* soil samples are as follows:

$$\bar{C}_{Cs} = \frac{1}{N}\sum_{i=1}^{N} C_{Cs,i} = \frac{1}{N \cdot \varepsilon_{Cs}}\sum_{i=1}^{N} \frac{R_{Cs,i}}{m_i} \qquad \textbf{Equation K-16}$$

$$\bar{C}_{Co} = \frac{1}{N}\sum_{i=1}^{N} C_{Co,i} = \frac{1}{N \cdot \varepsilon_{Co}}\sum_{i=1}^{N} \frac{R_{Co,i}}{m_i} \qquad \textbf{Equation K-17}$$

where:

$C_{Cs,i}$ = activity concentration of ^{137}Cs in the ith soil sample (Bq kg^{-1})
ε_{Cs} = detector efficiency for ^{137}Cs (cps Bq^{-1})
$R_{Cs,i}$ = net count rate for ^{137}Cs for the ith soil sample (cps)
$C_{Co,i}$ = activity concentration of ^{60}Co in the ith soil sample (Bq kg^{-1})
ε_{Co} = detector efficiency for ^{60}Co (cps Bq^{-1})
$R_{Co,i}$ = net count rate for ^{60}Co for the ith soil sample (cps)
m_i = mass of the ith sample (kg)

The average activity concentration of ^{137}Cs in the 10 soil samples is as follows:

$$\begin{aligned}\bar{C}_{Cs} &= \frac{1}{N}\sum_{i=1}^{N} C_{Cs,i} \\ &= \frac{1}{10}[172 \text{ Bq kg}^{-1} + \cdots + 61 \text{ Bq kg}^{-1}] \\ &= 138.3 \text{ Bq kg}^{-1}\end{aligned}$$

The average activity concentration of ^{60}Co in the 10 soil samples is as follows:

$$\begin{aligned}\bar{C}_{Co} &= \frac{1}{N}\sum_{i=1}^{N} C_{Co,i} \\ &= \frac{1}{10}[76 \text{ Bq kg}^{-1} + \cdots + 31 \text{ Bq kg}^{-1}] \\ &= 52.9 \text{ Bq kg}^{-1}\end{aligned}$$

Step 6 is to determine the combined standard uncertainty of the estimate of the measurand. The absolute uncertainties in the average activity concentrations of ^{137}Cs, $u_c(\bar{C}_{\mathrm{Cs}})$, and ^{60}Co, $u_c(\bar{C}_{\mathrm{Co}})$, in the N soil samples are given by the following:

$$u_c^2(\bar{C}_{\mathrm{Cs}}) = \sum_{i=1}^{N} \left(\frac{\partial \bar{C}_{\mathrm{Cs}}}{\partial R_{\mathrm{Cs},i}}\right)^2 u^2(R_{\mathrm{Cs},i}) + \left(\frac{\partial \bar{C}_{\mathrm{Cs}}}{\partial \varepsilon_{\mathrm{Cs}}}\right)^2 u^2(\varepsilon_{\mathrm{Cs}}) + \sum_{i=1}^{N} \left(\frac{\partial \bar{C}_{\mathrm{Cs}}}{\partial m_i}\right)^2 u^2(m_i) \qquad \textbf{Equation K-18}$$

$$u_c^2(\bar{C}_{\mathrm{Co}}) = \sum_{i=1}^{N} \left(\frac{\partial \bar{C}_{\mathrm{Co}}}{\partial R_{\mathrm{Co},i}}\right)^2 u^2(R_{\mathrm{Co},i}) + \left(\frac{\partial \bar{C}_{\mathrm{Co}}}{\partial \varepsilon_{\mathrm{Co}}}\right)^2 u^2(\varepsilon_{\mathrm{Co}}) + \sum_{i=1}^{N} \left(\frac{\partial \bar{C}_{\mathrm{Co}}}{\partial m_i}\right)^2 u^2(m_i) \qquad \textbf{Equation K-19}$$

where:

$u(R_{\mathrm{Cs},i})$ = absolute uncertainty in the net count rate for ^{137}Cs for the ith soil sample (cps)

$u(\varepsilon_{\mathrm{Cs}})$ = absolute uncertainty in the detector efficiency for ^{137}Cs (cps Bq^{-1})

$u(R_{\mathrm{Co},i})$ = absolute uncertainty in the net count rate for ^{60}Co for the ith soil sample (cps)

$u(\varepsilon_{\mathrm{Co}})$ = absolute uncertainty in the detector efficiency for ^{60}Co (cps Bq^{-1})

$u(m_i)$ = absolute uncertainty in the mass of the ith sample (kg)

Evaluating the partial derivatives—

$$\frac{\partial \bar{C}_{\mathrm{Cs}}}{\partial R_{\mathrm{Cs},i}} = \frac{1}{N \cdot \varepsilon_{\mathrm{Cs}} \cdot m_i} \qquad \frac{\partial \bar{C}_{\mathrm{Co}}}{\partial R_{\mathrm{Co},i}} = \frac{1}{N \cdot \varepsilon_{\mathrm{Co}} \cdot m_i}$$

$$\frac{\partial \bar{C}_{\mathrm{Cs}}}{\partial \varepsilon_{\mathrm{Cs}}} = \frac{-1}{N \cdot \varepsilon_{\mathrm{Cs}}^2} \sum_{i=1}^{N} \frac{R_{\mathrm{Cs},i}}{m_i} \qquad \frac{\partial \bar{C}_{\mathrm{Co}}}{\partial \varepsilon_{\mathrm{Co}}} = \frac{-1}{N \cdot \varepsilon_{\mathrm{Co}}^2} \sum_{i=1}^{N} \frac{R_{\mathrm{Co},i}}{m_i}$$

$$\frac{\partial \bar{C}_{\mathrm{Cs}}}{\partial m_i} = \frac{-R_{\mathrm{Cs},i}}{N \cdot \varepsilon_{\mathrm{Cs}} \cdot m_i^2} \qquad \frac{\partial \bar{C}_{\mathrm{Co}}}{\partial m_i} = \frac{-R_{\mathrm{Co},i}}{N \cdot \varepsilon_{\mathrm{Co}} \cdot m_i^2}$$

Substituting the partial derivatives into **Equation K-18** and **Equation K-19** and simplifying, the standard uncertainties of the average activity concentrations of ^{137}Cs, $u_c(\bar{C}_{\mathrm{Cs}})$, and ^{60}Co, $u_c(\bar{C}_{\mathrm{Co}})$, in the *N* soil samples are given by the following:

$$u_c^2(\bar{C}_{\mathrm{Cs}}) = \bar{C}_{\mathrm{Cs}}^2 \varphi^2(\varepsilon_{\mathrm{Cs}}) + \frac{1}{N^2} \sum_{i=1}^{N} C_{\mathrm{Cs},i}^2 [\varphi^2(R_{\mathrm{Cs},i}) + \varphi^2(m_i)] \qquad \textbf{Equation K-20}$$

$$u_c^2(\bar{C}_{\mathrm{Co}}) = \bar{C}_{\mathrm{Co}}^2 \varphi^2(\varepsilon_{\mathrm{Co}}) + \frac{1}{N^2} \sum_{i=1}^{N} C_{\mathrm{Co},i}^2 [\varphi^2(R_{\mathrm{Co},i}) + \varphi^2(m_i)] \qquad \textbf{Equation K-21}$$

Taking the square root of both sides of **Equation K-20** and **Equation K-21**, the absolute uncertainties of the average activity concentrations of ^{137}Cs, $u_c(\bar{C}_{\mathrm{Cs}})$, and ^{60}Co, $u_c(\bar{C}_{\mathrm{Co}})$, in the *N* soil samples are as follows:

$$u_c(\bar{C}_{Cs}) = \sqrt{\bar{C}_{Cs}{}^2 \left[\frac{u^2(\varepsilon_{Cs})}{\varepsilon_{Cs}{}^2}\right] + \frac{1}{N^2}\sum_{i=1}^{N} C_{Cs,i}{}^2 \left[\frac{u^2(R_{Cs,i})}{R_{Cs,i}{}^2} + \frac{u^2(m_i)}{m_i{}^2}\right]} \qquad \textbf{Equation K-22}$$

$$u_c(\bar{C}_{Co}) = \sqrt{\bar{C}_{Co}{}^2 \left[\frac{u^2(\varepsilon_{Co})}{\varepsilon_{Co}{}^2}\right] + \frac{1}{N^2}\sum_{i=1}^{N} C_{Co,i}{}^2 \left[\frac{u^2(R_{Co,i})}{R_{Co,i}{}^2} + \frac{u^2(m_i)}{m_i{}^2}\right]} \qquad \textbf{Equation K-23}$$

where:

$\bar{C}_{Cs}$ = average activity concentration of ^{137}Cs in the 10 soil samples (Bq kg^{-1})

$u(\varepsilon_{Cs})$ = standard uncertainty in the detector efficiency for ^{137}Cs (cps Bq-1)

ε_{Cs} = detector efficiency for ^{137}Cs (cps Bq-1)

$u(R_{Cs,i})$ = standard uncertainty in the net count rate for ^{137}Cs for the ith soil sample (cps)

$R_{Cs,i}$ = net count rate for ^{137}Cs for the ith soil sample (cps)

$\bar{C}_{Co}$ = average activity concentration of ^{60}Co in the 10 soil samples (Bq kg^{-1})

$u(\varepsilon_{Co})$ = standard uncertainty in the detector efficiency for ^{60}Co (cps Bq-1)

ε_{Co} = standard uncertainty in the detector efficiency for ^{60}Co (cps Bq-1)

$u(R_{Co,i})$ = standard uncertainty in the net count rate for ^{60}Co for the ith soil sample (cps)

$R_{Co,i}$ = standard uncertainty in the net count rate for ^{60}Co for the ith soil sample (cps)

$u(m_i)$ = standard uncertainty in the mass of the ith sample (kg)

m_i = mass of the ith sample (kg)

The standard uncertainty for the average activity concentration of ^{137}Cs for the 10 samples is as follows:

$$u_c(\bar{C}_{Cs}) = \{\bar{C}_{Cs}{}^2 \left[\frac{u^2(\varepsilon_{Cs})}{\varepsilon_{Cs}{}^2}\right] + \frac{1}{N^2}\sum_{i=1}^{N} C_{Cs,i}{}^2 \left[\frac{u^2(R_{Cs,i})}{R_{Cs,i}{}^2} + \frac{u^2(m_i)}{m_i{}^2}\right]\}^{½}$$

$$= \{ (138.3 \text{ Bq kg}^{-1})^2 \left(\frac{0.002 \text{ cps Bq}^{-1}}{0.135 \text{ cps Bq}^{-1}}\right)^2 + \frac{1}{10^2}\left[(172 \text{ Bq kg}^{-1})^2 \left[\left(\frac{1.28 \text{ cps}}{11.60 \text{ cps}}\right)^2 + \left(\frac{0.005 \text{ kg}}{0.500 \text{ kg}}\right)^2\right] + \cdots + (61 \text{ Bq kg}^{-1})^2 \left[\left(\frac{1.23 \text{ cps}}{4.23 \text{ cps}}\right)^2 + \left(\frac{0.005 \text{ kg}}{0.513 \text{ kg}}\right)^2\right]\right]\}^{½}$$

$$= 6.4 \text{ Bq kg}^{-1}$$

The standard uncertainty for the average activity concentration of ^{60}Co for the 10 samples is as follows:

$$u_c(\bar{C}_{\text{Co}}) = \{\bar{C}_{\text{Co}}^2 \left[\frac{u^2(\varepsilon_{\text{Co}})}{\varepsilon_{\text{Co}}^2}\right] + \frac{1}{N^2}\sum_{i=1}^{N} C_{\text{Co},i}^2 \left[\frac{u^2(R_{\text{Co},i})}{R_{\text{Co},i}^2} + \frac{u^2(m_i)}{m_i^2}\right]\}^{½}$$

$$= \{ (52.9 \text{ Bq kg}^{-1})^2 \left(\frac{0.002 \text{ cps Bq}^{-1}}{0.101 \text{ cps Bq}^{-1}}\right)^2 + \frac{1}{10^2}\left[(76 \text{ Bq kg}^{-1})^2 \left[\left(\frac{0.86 \text{ cps}}{3.83 \text{ cps}}\right)^2 + \left(\frac{0.005 \text{ kg}}{0.500 \text{ kg}}\right)^2\right] + \cdots + (31 \text{ Bq kg}^{-1})^2 \left[\left(\frac{0.86 \text{ cps}}{1.60 \text{ cps}}\right)^2 + \left(\frac{0.005 \text{ kg}}{0.513 \text{ kg}}\right)^2\right]\right]\}^{½}$$

$$= 5.5 \text{ Bq kg}^{-1}$$

Step 7 is to optionally multiply the combined standard uncertainty of the estimate of the measurand by a coverage factor, k, to obtain the expanded uncertainty to construct an interval that can be expected to contain the true value of the measurand with a specified (high) probability. The reported standard uncertainty or expanded uncertainty should usually be rounded to two significant figures and the estimate of the measurand rounded to the same number of digits. The values calculated before rounding should be used in any subsequent calculations to avoid rounding errors.

Step 8 is to report the result as the estimate of the measurand ± the expanded uncertainty, together with the unit of measurement, and, at a minimum, to state the coverage factor used to compute the expanded uncertainty and the estimated coverage probability.

The estimated activity concentration can be reported as follows:

$$\bar{C}_{\text{Cs}} \pm k \cdot u_C(\bar{C}_{\text{Cs}}) \qquad \textbf{Equation K-24}$$

$$\bar{C}_{\text{Co}} \pm k \cdot u_C(\bar{C}_{\text{Co}}) \qquad \textbf{Equation K-25}$$

where k is a coverage factor to obtain the expanded uncertainty, such that the interval $[\bar{C}_{\text{Cs}} - k \cdot u_C(\bar{C}_{\text{Cs}}),\ \bar{C}_{\text{Cs}} + k \cdot u_C(\bar{C}_{\text{Cs}})]$ or $[\bar{C}_{\text{Co}} - k \cdot u_C(\bar{C}_{\text{Co}}),\ \bar{C}_{\text{Co}} + k \cdot u_C(\bar{C}_{\text{Co}})]$ can be expected to contain the value of the measurand with a specified (high) probability.

Using a coverage factor of 2 and an estimated coverage probability of 95 percent, the estimated average activity concentration of ^{137}Cs is (138 ± 13) Bq kg^{-1}. The average activity concentration of ^{60}Co is (53 ± 11) Bq kg^{-1}, again using a coverage factor of 2 and an estimated coverage probability of 95 percent.

The uncertainties estimated in **Equation K-22** and **Equation K-23** are the uncertainties in the average of the average concentrations of ^{137}Cs and ^{60}Co, respectively, at the 10 locations selected. It is the uncertainty in the average concentrations if soil samples were taken at the same 10 locations again. To better estimate the uncertainties in the average concentrations, including the spatial variability of the average concentrations, the sample standard deviation can be used to estimate the uncertainty in the average concentrations (using the concentration data in **Table K-3**):

$$u_c(\bar{C}_{\text{Cs}}) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(C_{Cs,i} - \bar{C}_{Cs})^2} \qquad \textbf{Equation K-26}$$

$$= \{\frac{1}{10-1}[(172 \text{ Bq kg}^{-1} - 138 \text{ Bq kg}^{-1})^2 + \cdots + (61 \text{ Bq kg}^{-1} - 138 \text{ Bq kg}^{-1})^2]\}^{½}$$

$$= 48 \text{ Bq kg}^{-1}$$

$$u_c^2(\bar{C}_{\text{Co}}) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(C_{Co,i} - \bar{C}_{Co})^2} \qquad \textbf{Equation K-27}$$

$$= \{\frac{1}{10-1}[(76 \text{ Bq kg}^{-1} - 53 \text{ Bq kg}^{-1})^2 + \cdots + (31 \text{ Bq kg}^{-1} - 53 \text{ Bq kg}^{-1})^2]\}^{½}$$

$$= 21 \text{ Bq kg}^{-1}$$

Using the sample standard deviation, the average concentrations of ^{137}Cs and ^{60}Co can be reported as 138 ± 97 Bq kg^{-1} and 53 ± 42 Bq kg^{-1}, respectively, with a coverage factor of k = 2.

Task 4: Average Sum of Fractions in Soil Samples

Step 1 is to identify the measurand and all the input quantities for the mathematical measurement model. The measurand is the average sum of fractions for the 10 soil samples. The input quantities are the net count rates, spectrometer efficiencies, sample masses, and DCGLs.

Step 2 is to determine an estimate of the value of each input quantity. The spectrometer efficiencies are given as 0.135 cps Bq^{-1} and 0.101 cps Bq^{-1} for ^{137}Cs and ^{60}Co, respectively. The DCGLs are given as 350 Bq kg^{-1} and 90 Bq kg^{-1} for ^{137}Cs and ^{60}Co, respectively. **Table K-1** provides estimates for the values of the net count rates and sample masses.

Step 3 is to evaluate the standard uncertainty for each input estimate using either a Type A or Type B method of evaluation. The standard uncertainties in spectrometer efficiencies are given

as 0.002 cps Bq^{-1} and 0.002 cps Bq^{-1} for ^{137}Cs and ^{60}Co, respectively. The DCGLs are assumed to be free of uncertainty. **Table K-1** shows the standard uncertainties for net count rates and sample masses.

Step 4 is to evaluate the covariances for all pairs of input estimates with potentially significant correlations. The input variables are independent, and there are no correlations between any pairs of input estimates.

Step 5 is to calculate the estimate of the measurand from the mathematical measurement model determined in Step 1. The average sum of fractions for the *N* soil samples, $\bar{T}$, is as follows:

$$\bar{T} = \frac{\bar{C}_{Cs}}{DCGL_{Cs}} + \frac{\bar{C}_{Co}}{DCGL_{Co}} = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{m_i}\left[\frac{R_{Cs,i}}{\varepsilon_{Cs}\cdot DCGL_{Cs}} + \frac{R_{Co,i}}{\varepsilon_{Co}\cdot DCGL_{Co}}\right] \qquad \textbf{Equation K-28}$$

where:

$\bar{C}_{Cs}$ = average activity concentration of ^{137}Cs in the 10 soil samples (Bq kg^{-1})
$DCGL_{Cs}$ = $DCGL_W$ for ^{137}Cs (Bq kg^{-1})
$R_{Cs,i}$ = net count rate for ^{137}Cs for the ith soil sample (cps)
ε_{Cs} = detector efficiency for ^{137}Cs (cps Bq^{-1})
$\bar{C}_{Co}$ = average activity concentration of ^{60}Co in the 10 soil samples (Bq kg^{-1})
$DCGL_{Co}$ = $DCGL_W$ for ^{60}Co (Bq kg^{-1})
$R_{Co,i}$ = net count rate for ^{60}Co for the ith soil sample (cps)
ε_{Co} = detector efficiency for ^{60}Co (cps Bq^{-1})
m_i = mass of the ith sample (kg)

The standard uncertainty of the average sum of fractions for the *N* soil samples, $u_c(\bar{T})$, is given by the following:

$$u_c^2(\bar{T}) = \sum_{i=1}^{N}\left(\frac{\partial\bar{T}}{\partial R_{Cs,i}}\right)^2 u^2(R_{Cs,i}) + \left(\frac{\partial\bar{T}}{\partial\varepsilon_{Cs}}\right)^2 u^2(\varepsilon_{Cs}) + \sum_{i=1}^{N}\left(\frac{\partial\bar{T}}{\partial R_{Co,i}}\right)^2 u^2(R_{Co,i}) \qquad \textbf{Equation K-29}$$

$$+ \left(\frac{\partial\bar{T}}{\partial\varepsilon_{Co}}\right)^2 u^2(\varepsilon_{Co}) + \sum_{i=1}^{N}\left(\frac{\partial\bar{T}}{\partial m_i}\right)^2 u^2(m_i)$$

where:

$u(R_{Cs,i})$ = absolute uncertainty in the net count rate for ^{137}Cs for the ith soil sample (cps)

$u(\varepsilon_{Cs})$ = absolute uncertainty in the detector efficiency for ^{137}Cs (cps Bq^{-1})

$u(R_{Co,i})$ = absolute uncertainty in the net count rate for ^{60}Co for the ith soil sample (cps)

$u(\varepsilon_{Co})$ = absolute uncertainty in the detector efficiency for ^{60}Co (cps Bq^{-1})

$u(m_i)$ = absolute uncertainty in the mass of the ith sample (kg)

Evaluating the partial derivatives—

$$\frac{\partial \bar{T}}{\partial R_{\mathrm{Cs},i}} = \frac{1}{N \cdot m_i \cdot \varepsilon_{\mathrm{Cs}} \cdot \mathrm{DCGL}_{\mathrm{Cs}}} \qquad \frac{\partial \bar{T}}{\partial \varepsilon_{\mathrm{Co}}} = \frac{-1}{N \cdot \varepsilon_{\mathrm{Co}}{}^2 \cdot \mathrm{DCGL}_{\mathrm{Co}}} \sum_{i=1}^{N} \frac{R_{\mathrm{Co},i}}{m_i}$$

$$\frac{\partial \bar{T}}{\partial \varepsilon_{\mathrm{Cs}}} = \frac{-1}{N \cdot \varepsilon_{\mathrm{Cs}}{}^2 \cdot \mathrm{DCGL}_{\mathrm{Cs}}} \sum_{i=1}^{N} \frac{R_{\mathrm{Cs},i}}{m_i} \qquad \frac{\partial \bar{T}}{\partial m_i} = \frac{-1}{N \cdot m_i{}^2} \left[\frac{R_{\mathrm{Cs},i}}{\varepsilon_{\mathrm{Cs}} \cdot \mathrm{DCGL}_{\mathrm{Cs}}} + \frac{R_{\mathrm{Co},i}}{\varepsilon_{\mathrm{Co}} \cdot \mathrm{DCGL}_{\mathrm{Co}}}\right]$$

$$\frac{\partial \bar{T}}{\partial R_{\mathrm{Co},i}} = \frac{1}{N \cdot m_i \cdot \varepsilon_{\mathrm{Co}} \cdot \mathrm{DCGL}_{\mathrm{Co}}}$$

Substituting the partial derivatives into **Equation K-29** and simplifying, the absolute uncertainty of the average sum of fractions for the *N* soil samples, $u_c(\bar{T})$, is given by the following:

$$u_c^2(\bar{T}) = \frac{1}{N^2} \sum_{i=1}^{N} \left[\left(\frac{C_{\mathrm{Cs},i}}{\mathrm{DCGL}_{\mathrm{Cs}}}\right)^2 \frac{\varphi^2(R_{\mathrm{Cs},i})}{R_{\mathrm{Cs},i}{}^2} + \left(\frac{C_{\mathrm{Co},i}}{\mathrm{DCGL}_{\mathrm{Co}}}\right)^2 \frac{\varphi^2(R_{\mathrm{Co},i})}{R_{\mathrm{Co},i}{}^2} + T_i{}^2 \frac{\varphi^2(m_i)}{m_i{}^2}\right] \qquad \textbf{Equation K-30}$$

$$+ \left(\frac{\bar{C}_{\mathrm{Cs}}}{\mathrm{DCGL}_{\mathrm{Cs}}}\right)^2 \frac{\varphi^2(\varepsilon_{\mathrm{Cs}})}{\varepsilon_{\mathrm{Cs}}{}^2} + \left(\frac{\bar{C}_{\mathrm{Co}}}{\mathrm{DCGL}_{\mathrm{Co}}}\right)^2 \frac{\varphi^2(\varepsilon_{\mathrm{Co}})}{\varepsilon_{\mathrm{Co}}{}^2}$$

Taking the square root of both sides of **Equation K-30**, the absolute uncertainty of the average sum of fractions for the *N* soil samples, $u_c(\bar{T})$, is as follows:

$$u_c(\bar{T}) = \left\{ \begin{array}{c} \frac{1}{N^2} \sum_{i=1}^{N} \left[\left(\frac{C_{\mathrm{Cs},i}}{\mathrm{DCGL}_{\mathrm{Cs}}}\right)^2 \varphi^2(R_{\mathrm{Cs},i}) + \left(\frac{C_{\mathrm{Co},i}}{\mathrm{DCGL}_{\mathrm{Co}}}\right)^2 \varphi^2(R_{\mathrm{Co},i}) + T_i{}^2 \varphi^2(m_i)\right] \\ + \left(\frac{\bar{C}_{\mathrm{Cs}}}{\mathrm{DCGL}_{\mathrm{Cs}}}\right)^2 \varphi^2(\varepsilon_{\mathrm{Cs}}) + \left(\frac{\bar{C}_{\mathrm{Co}}}{\mathrm{DCGL}_{\mathrm{Co}}}\right)^2 \varphi^2(\varepsilon_{\mathrm{Co}}) \end{array} \right\}^{1/2} \qquad \textbf{Equation K-31}$$

where:

$u(R_{\mathrm{Cs},i})$ = standard uncertainty in the net count rate for ^{137}Cs for the ith soil sample (cps)

$R_{\mathrm{Cs},i}$ = net count rate for ^{137}Cs for the ith soil sample (cps)

$u(\varepsilon_{\mathrm{Cs}})$ = standard uncertainty in the detector efficiency for ^{137}Cs (cps Bq^{-1})

$\varepsilon_{\mathrm{Cs}}$ = detector efficiency for ^{137}Cs (cps Bq^{-1})

$u(R_{\mathrm{Co},i})$ = standard uncertainty in the net count rate for ^{60}Co for the ith soil sample (cps)

$R_{\mathrm{Co},i}$ = net count rate for ^{60}Co for the ith soil sample (cps)

$u(\varepsilon_{\mathrm{Co}})$ = standard uncertainty in the detector efficiency for ^{60}Co (cps Bq^{-1})

$\varepsilon_{\mathrm{Co}}$ = detector efficiency for ^{60}Co (cps Bq^{-1})

$\varphi(m_i)$ = standard uncertainty in the mass of the ith sample (kg)

m_i = mass of the ith sample (kg)

Step 7 is to optionally multiply the combined standard uncertainty of the estimate of the measurand by a coverage factor, *k*, to obtain the expanded uncertainty to construct an interval that can be expected to contain the true value of the measurand with a specified (high) probability. The reported standard uncertainty or expanded uncertainty should usually be rounded to two significant figures and the estimate of the measurand rounded to the same number of digits. The values calculated before rounding should be used in any subsequent calculations to avoid rounding errors.

Step 8 is to report the result as the estimate of the measurand ± the expanded uncertainty, together with the unit of measurement, and, at a minimum, to state the coverage factor used to compute the expanded uncertainty and the estimated coverage probability.

The average sum of fractions is 0.983, and the combined standard uncertainty, rounded to two significant figures, is 0.064. The estimated activity concentration can be reported as follows:

$$\bar{T} \pm k \cdot u_C(\bar{T}) \qquad \textbf{Equation K-32}$$

where k is a coverage factor to obtain the expanded uncertainty, such that the interval $[\bar{T} - k \cdot u_C(\bar{T}),\ \bar{T} + k \cdot u_C(\bar{T})]$ can be expected to contain the value of the measurand with a specified (high) probability. Using a coverage factor of 2 and an estimated coverage probability of 95 percent, the average sum of fractions can be reported as 0.983 ± 0.13 with a coverage factor of *k* = 2.

The uncertainty estimated in **Equation K-32** is the uncertainty in the average of the sum of fractions at the 10 locations selected. It is the uncertainty in the sum of fractions if soil samples were taken at the same 10 locations again. To better estimate the uncertainty in the sum of fractions, including the spatial variability of the sum of fractions, the sample standard deviation can be used to estimate the uncertainty in the sum of fractions (using the sum of fractions data in **Table K-3**):

$$u_c^2(\bar{T}) = \frac{1}{N-1}\sum_{i=1}^{N}(T_i - \bar{T})^2 \qquad \textbf{Equation K-33}$$

$$= \frac{1}{10-1}[(1.334 - 0.983)^2 + \cdots + (0.517 - 0.983)^2]$$

$$= 0.32$$

Using the sample standard deviation, the average sum of fractions can be reported as 1.0 ± 0.6 with a coverage factor of *k* = 2.

APPENDIX L
STEM AND LEAF DISPLAYS AND QUANTILE PLOTS

L.1 Stem and Leaf Display

The construction of a stem and leaf display is a simple way to quickly generate a crude histogram of the data. The "stems" of such a display are the most significant digits of the data. Consider the sample data in **Section 8.2.2.1:**

90.7, 83.5, 86.4, 88.5, 84.4, 74.2, 84.1, 87.6, 78.2, 77.6,
86.4, 76.3, 86.5, 77.4, 90.3, 90.1, 79.1, 92.4, 75.5, 80.5

Here, the data span three decades, so one might consider using the stems 70, 80, and 90. However, three are too few stems to be informative, just as three intervals would be too few to construct a histogram. Therefore, for this example, each decade is divided into two parts. This results in the six stems 70, 75, 80, 85, 90, 95. The leaves are the least significant digits, so 90.7 has the stem 90 and the leaf 0.7. Similarly, 77.4 has the stem 75 and the leaf 7.4. Note that even though the stem is 75, the leaf is *not* 2.4. The leaf is kept as 7.4 so that the data can be read directly from the display without any calculations.

As shown in the top part of **Figure L-1**, simply arrange the leaves of the data into rows, one stem per row. The result is a quick histogram of the data. The same number of digits should[1] be used for each leaf, so that each occupies the same amount of horizontal space.

If the stems are arranged in increasing order, as shown in the bottom half of **Figure L-1,** it is easy to pick out the minimum (74.2), the maximum (92.4), and the median (between 84.1 and 84.4).

Stem	Leaves
70	4.2
75	8.2, 7.6, 6.3, 7.4, 9.1, 5.5
80	3.5, 4.4, 4.1, 0.5
85	6.4, 8.5, 7.6, 6.4, 6.5
90	0.7, 0.3, 0.1, 2.4
95	

Stem	Sorted Leaves
70	4.2
75	5.5, 6.3, 7.4, 7.6, 8.2, 9.1
80	0.5, 3.5, 4.1, 4.4
85	6.4, 6.4, 6.5, 7.6, 8.5
90	0.1, 0.3, 0.7, 2.4
95	

Figure L-1 Example of a Stem and Leaf Display

[1] The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

A stem and leaf display (or histogram) with two peaks may indicate that residual radioactive material is distributed over only a portion of the survey unit. EPA QA/G-9S, "Data Quality Assessment: Statistical Methods for Practitioners," issued February 2006 (EPA 2006b), contains more information on the construction and interpretation of data plots.

L.2 Quantile Plots

A quantile plot is constructed by first ranking the data from smallest to largest. Sorting the data is easy once the stem and leaf display has been constructed. Then, each data value is simply plotted against the percentage of the samples with that value or less. This percentage is computed from **Equation L-1:**

$$\text{Percent} = \frac{100\ (\text{rank} - 0.5)}{(\text{number of data points})} \qquad \textbf{Equation L-1}$$

The slope of the curve in the quantile plot indicates the amount of data in a given range of values. A small amount of data in a range will result in a large slope. A large amount of data in a range between the lowest and highest values will result in a more horizontal slope. A sharp rise near the bottom or the top is an indication of asymmetry. Sudden changes in slope, or notably flat or notably steep areas, may indicate peculiarities in the survey unit data needing further investigation.

Table L-1 shows the results using **Equation L-1** for the example data in **Section L.1.**

Table L-1 Data for Quantile Plot

Data:	74.2	75.5	76.3	77.4	77.6	78.2	79.1	80.5	83.5	84.1
Rank:	1	2	3	4	5	6	7	8	9	10
Percent:	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5
Data:	84.4	86.4	86.4	86.5	87.6	88.5	90.1	90.3	90.7	92.4
Rank:	11	12.5	12.5	14	15	16	17	18	19	20
Percent:	52.5	60.0	60.0	67.5	72.5	77.5	82.5	87.5	92.5	97.5

Figure L-2 shows the quantile plot for this example. A useful aid to interpreting the quantile plot is the addition of boxes containing the middle 50 percent and middle 75 percent of the data. **Figure L-2** shows these as dashed lines. The 50 percent box has its upper right corner at the 75th percentile and its lower left corner at the 25th percentile. These points are called the quartiles. These are ~78 (25th percentile) and ~88 (75th percentile) becquerels per kilogram (Bq/kg), as indicated by the dashed lines. They bracket the middle half of the data values. The 75 percent box has its upper right corner at the 87.5th percentile and its lower left corner at the 12.5th percentile. A sharp increase within the 50 percent box can indicate two or more modes in the data. Outside the 75 percent box, sharp increases can indicate outliers. The median (50th percentile) is indicated by the heavy solid line at the value ~84 and can be used as an aid in judging the symmetry of the data distribution. The example quantile plot shown in **Figure L-2** has no especially unusual features, other than the possibility of slight asymmetry around the median.

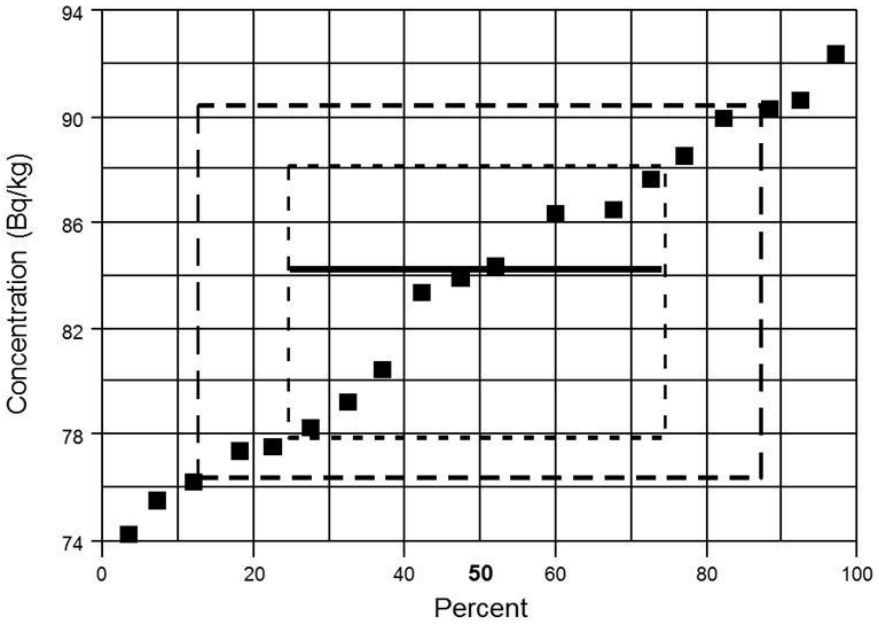

Figure L-2 Example of a Quantile Plot for the Data in Table L-1

Figure L-3 shows a quantile plot for the example data in **Section 8.3.2, Table 8-8.**

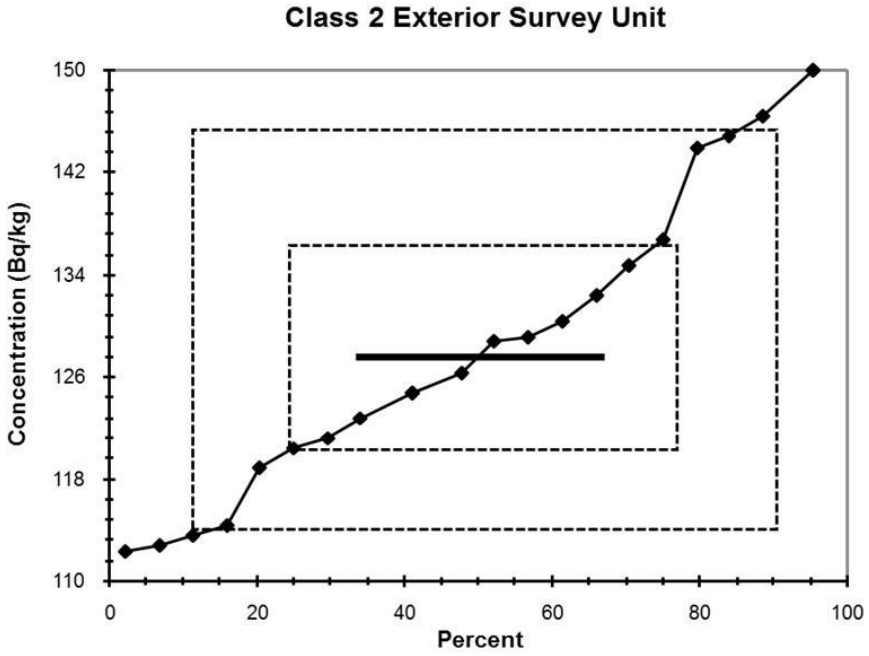

Figure L-3 Quantile Plot for Example Class 2 Exterior Survey Unit in Section 8.3.2, Table 8-9 (concentration in Bq/kg)

A **quantile-quantile** plot is extremely useful for comparing two sets of data. Suppose the following 17 concentration values were obtained in a reference area corresponding to the example survey unit data used in **Figure L-2:**

92.1, 83.2, 81.7, 81.8, 88.5, 82.4, 81.5, 69.7, 82.4, 89.7,
81.4, 79.4, 82.0, 79.9, 81.1, 59.4, 75.3

A quantile-quantile plot can be constructed to compare the distribution of the survey unit data, Y_j, $j = 1,\ldots n$, with the distribution of the reference area data X_i , $i = 1,\ldots m$. (If the reference area dataset was the larger of the two, the roles of X and Y would be reversed.) The data from each set are ranked separately from smallest to largest. This has already been done for the survey unit data in **Table L-1.** For the reference area data, **Table L-2** shows the results obtained**.**

Table L-2 Ranked Reference Area Concentrations

Data:	59.4	69.7	75.3	79.4	79.9	81.1	81.4	81.5	81.7	81.8
Rank:	1	2	3	4	5	6	7	8	9	10
Data:	82.0	82.4	82.4	83.2	88.5	89.7	92.1	—	—	—
Rank:	11	12.5	12.5	14	15	16	17	—	—	—

The median for the reference area data is 81.7, the sample mean[2] is 80.7, and the sample standard deviation is 7.5.

For the larger dataset, the data must be interpolated to match the number of points in the smaller dataset. This is done by computing v_i as shown in **Equation L-2:**

$$v_1 = 0.5(^n/_m) + 0.5 \text{ and } v_{i+1} = v_i + (^n/_m) \text{ for } i = 1,\cdots m \qquad \textbf{Equation L-2}$$

where *m* is the number of points in the smaller dataset and *n* is the number of points in the larger dataset. For each of the ranks, i, in the smaller dataset, a corresponding value in the larger dataset is found by first decomposing v_i into its integer part, j, and its fractional part, g.

Then, the interpolated values are computed from the relationship in **Equation L-3:**

$$\mathrm{Z_i} = (1-\mathrm{g})\mathrm{Y_j} + \mathrm{gY_{j+1}} \qquad \textbf{Equation L-3}$$

Table L-3 shows the results of these calculations using survey unit data values from **Table L-1** for the Y_j values in **Equation L-3**. For this example, implementation of **Equation L-2** results in v_i from i = 1 to 17 with integer components of v_i (i.e., the j values) equal to 1–6, 8–12, and 14–19 (i.e., integer values 7 and 13 are skipped and integer value 20 is not calculated). **Equation L-3** applies a weighted average of two consecutive data points listed in **Table L-1** with the two data points to be averaged determined by the ranks, j and j+1. As a result of this process, the number of survey unit data values are reduced from the initial 20 values to the final 17 values. This technique establishes a one-to-one relationship between the survey unit and reference area data that can be plotted in a quantile-quantile plot.

To produce the quantile plot, Z_i is plotted against X_i (see calculated Z_i values and ranked reference area measurements [X_i] in **Table L-3**). **Figure L-4** shows this example from **Table L-3.** The quantile-quantile plot is valuable because it provides a direct visual comparison

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[2] In MARSSIM, “average” and “mean” both refer to the arithmetic mean.

of the two datasets. If the two data distributions differ only in location (e.g., mean) or scale (e.g., standard deviation), the points will lie on a straight line. If the two data distributions being compared are identical, all of the plotted points will lie on the line $Y = X$. Any deviations from this would point to possible differences in these distributions. The middle data point plots the median of Y against the median of X. That this point lies above the line $Y = X$, in the example of **Figure L-4**, shows that the median of Y is larger than the median of X. Indeed, the cluster of points above the line $Y = X$ in the region of the plot where the data points are dense indicates that the central portion of the survey unit distribution is shifted toward higher values than the reference area distribution. This could imply that there is residual radioactive material in the survey unit. This should be tested using the nonparametric statistical tests described in **Chapter 8.**

Figure A-9 shows another quantile-quantile plot for the Class 1 interior survey unit example data. EPA QA/G-9S (EPA 2006b) contains more information on the interpretation of quantile and quantile-quantile plots.

Table L-3 Interpolated Ranks for Survey Unit Concentrations

Rank	1	2	3	4	5	6	7	8	9	10
v_i	1.09	2.26	3.44	4.62	5.79	6.97	8.15	9.33	10.50	11.68
Z_i	74.3	75.7	76.8	77.5	78.1	79.1	80.9	83.7	84.3	85.8
X_i	59.4	69.7	75.3	79.4	79.7	81.1	81.4	81.5	81.7	81.8
Rank	11	12.5	12.5	14	15	16	17	—	—	—
v_i	12.85	14.03	15.21	16.38	17.56	18.74	19.91	—	—	—
Z_i	86.4	86.5	87.8	89.1	90.2	90.6	92.3	—	—	—
X_i	82.0	82.4	82.4	83.2	88.5	89.7	92.1	—	—	—

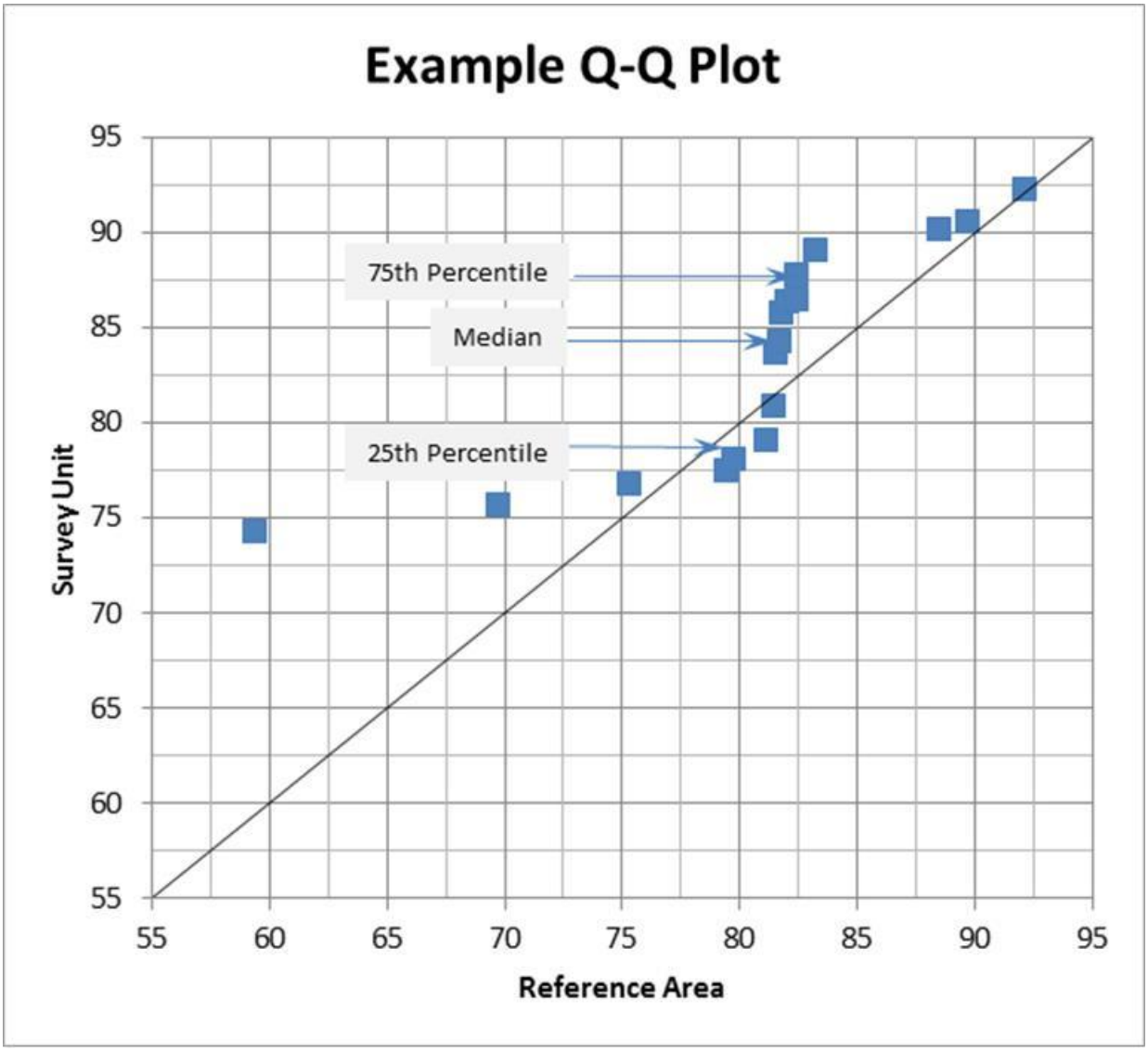

Figure L-4 Example Quantile-Quantile (Q-Q) Plot for Data in Table L-3

APPENDIX M
CALCULATION OF POWER CURVES

Appendix M provides instructions for calculating the prospective and retrospective statistical power for the following tests:

- Sign test under Scenario A
- Sign test under Scenario B
- Wilcoxon Rank Sum (WRS) test under Scenario A
- WRS test under Scenario B

For both the Sign test and the WRS test, the same method is used to calculate prospective and retrospective power curves. The difference is the way that inputs to the power analysis are estimated. For prospective curves, the variability of measurements is typically estimated from the results obtained during the scoping or characterization surveys, or both, and the number of measurements is determined during the design of the final status survey. For retrospective curves, the variability of measurements is typically estimated from the results obtained during the final status survey, and the number of measurements is equal to the actual number of measurements made.

For Scenario A, the power is the probability of rejecting the null hypothesis that the concentration of residual radioactive material is above the release criteria.

While a retrospective power analysis is not required for Scenario A, it can be useful, particularly when the result of the statistical test is to fail to reject the null hypothesis. The retrospective power analysis can provide insights to determine whether the failure to reject the null hypothesis was because the null hypothesis is true or because there was insufficient statistical power. The statistical power may be insufficient for one or more of the following reasons:

- The number of measurements or samples was less than that planned in designing the survey.

- The variability in the results of the measurements or samples was greater than that planned in designing the survey.

- The true value of the parameter of interest (e.g., activity concentration), while less than the derived concentration guideline level (DCGL) for average concentrations over a wide area ($DCGL_W$), is greater than that planned in designing the survey.

For Scenario B, the power is the probability of rejecting the null hypothesis that the concentration of residual radioactive material is below the release criteria. For Scenario B, the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) requires both a retrospective power analysis of the Sign or WRS test and performance of the Quantile test. While a power analysis of the Quantile test is not required by MARSSIM or described in this appendix, it can be performed if there is a question of whether the Quantile test has sufficient statistical power.

M.1 Sign Test

If the radionuclide is not part of the natural background and radionuclide-specific measurements will be made, MARSSIM recommends the Sign test.

M.1.1 Sign Test under Scenario A

The following steps can be used to calculate the power of the Sign test under Scenario A:

(1) For each value of *x*, calculate the relative shift (Δ/σ) using the following equation:

$$\Delta/\sigma = \mathrm{DCGL_W} - \mathrm{x}\sigma \qquad \textbf{Equation M-1}$$

where:

$\mathrm{DCGL_W}$ = wide-area dose concentration guideline level

x = true value of the parameter of interest (e.g., expected or average value of the survey unit)

Δ = shift (width of the gray region)

σ = variability of measurements in the survey unit, given as the standard deviation

(2) Set $N = n_s$ (the number of survey unit measurements).

(3) Look up the critical value, k, given in **Table I-4** for the appropriate values of N and α for the Sign test.

(4) For each value of Δ/σ, calculate $q^*(\Delta/\sigma)$ using the following equation:

$$q^*(\Delta/\sigma) = \Phi(\Delta/\sigma) \qquad \textbf{Equation M-2}$$

where $\Phi(z)$ is the standard normal cumulative distribution function tabulated in **Table I-1**.

(5) For each value of *x*, calculate the power, $1-\beta(x)$, using one of the following two equations (MARSSIM provides two methods to estimate the power of the Sign test: an exact method, as given in **Equation M-3**, and an approximate method, as given in **Equation M-4**):

$$1-\beta(x) = 1 - \sum_{i=0}^{k} \binom{N}{i} [q^*(\Delta/\sigma)]^i [1-q^*(\Delta/\sigma)]^{N-i} \qquad \textbf{Equation M-3}$$

$$1-\beta(x) \approx 1 - \Phi\left(\frac{k - N \cdot q^*(\Delta/\sigma)}{\sqrt{N[q^*(\Delta/\sigma)][1-q^*(\Delta/\sigma)]}}\right) \qquad \textbf{Equation M-4}$$

The following Microsoft Excel™ workbook formulae can be used to implement the approximate method:

q^* = NORM.S.DIST(Δ/σ,TRUE)

$1-\beta(x)$ = 1-NORM.S.DIST(((k-N*q^*)/(SQRT(N*q^***(1-q^*)))),TRUE)

Example M-1 shows the calculation of the power of the Sign test under Scenario A. While **Example M-1** shows examples of both methods for purposes of illustration, it is usually sufficient to calculate the power using one or the other, but not both.

Example M-1: Using Scenario A, the DCGL is 400 becquerels (Bq) per kilogram (kg^{-1}), the lower bound of the gray region (LBGR) is 200 Bq kg^{-1}, and the estimated standard deviation is 80 Bq kg^{-1}. The Type I error at the DCGL and the Type II error at the LBGR are both set at 0.05. The number of samples required for the Sign test is 15 ($N = 15$).

The relative shift, Δ/σ, at the LBGR of 200 Bq kg^{-1} is as follows:

$$\Delta/\sigma = \text{DCGL} - \text{LBGR}\sigma = \frac{400 \text{ Bq kg}^{-1} - 200 \text{ Bq kg}^{-1}}{80 \text{ Bq kg}^{-1}} = 2.5$$

For $N = 15$ and $\alpha = 0.05$, the critical value is 11 ($\mathrm{k} = 11$). The value of $q^*(\Delta/\sigma)$ at the LBGR is as follows:

$$q^*(\Delta/\sigma) = \Phi(\Delta/\sigma) = q^*(2.5) = \Phi(2.5) = 0.993\ 790$$

The exact power at the LBGR is as follows:

$$1 - \beta = 1 - \sum_{i=0}^{k} \binom{N}{i} [q^*(\Delta/\sigma)]^i [1 - q^*(\Delta/\sigma)]^{N-i}$$

$$= 1 - \sum_{i=0}^{k} \binom{15}{i} [q^*(2.5)]^i [1 - q^*(2.5)]^{15-i}$$

$$= 1 - \sum_{i=0}^{11} \frac{15!}{(15-i)!\, i!} [0.993\ 790]^i [1 - 0.993\ 790]^{15-i}$$

$$= 1 - \left(\frac{15!}{15!\, 0!} [0.993\ 790]^0 [1 - 0.993\ 790]^{15} + \cdots + \frac{15!}{4!\, 11!} [0.993\ 790]^{11} [1 - 0.993\ 790]^4 \right)$$

$$= 0.999\ 998$$

The approximate power at the LBGR is as follows:

$$1 - \beta \approx 1 - \Phi\left(\frac{k - N \cdot q^*(\Delta/\sigma)}{\sqrt{N[q^*(\Delta/\sigma)][1 - q^*(\Delta/\sigma)]}} \right)$$

$$\approx 1 - \Phi\left(\frac{11 - 15 \cdot q^*(2.5)}{\sqrt{15[q^*(2.5)][1 - q^*(2.5)]}} \right)$$

$$\approx 1 - \Phi\left(\frac{11 - 15 \cdot 0.993\ 790}{\sqrt{15[0.993\ 790][1 - 0.993\ 790]}} \right)$$

$$\approx 1.000\ 000$$

Table M-1 and **Figure M-1** show the results for the power curve calculation. **Figure M-2** and **Figure M-3** show the Visual Sample Plan (Version 7.19) user interface dialog box and power curve, respectively, for **Example M-1**.

Table M-1 Calculations for Example M-1 of the Power Curve for the Sign Test under Scenario A, Using Equations M-3 and M-4

True Activity Concentration [Bq kg^{-1}]	Δ/σ	$q^*(\Delta/\sigma)$	$1-\beta$ Approximate
0.0	5.00000	1.000 000	1.000 000
12.5	4.84375	0.999 999	1.000 000
25.0	4.68750	0.999 999	1.000 000
37.5	4.53125	0.999 997	1.000 000
50.0	4.37500	0.999 994	1.000 000
62.5	4.21875	0.999 988	1.000 000
75.0	4.06250	0.999 976	1.000 000
87.5	3.90625	0.999 953	1.000 000
100.0	3.75000	0.999 912	1.000 000
112.5	3.59375	0.999 837	1.000 000
125.0	3.43750	0.999 706	1.000 000
137.5	3.28125	0.999 483	1.000 000
150.0	3.12500	0.999 111	1.000 000
162.5	2.96875	0.998 505	1.000 000
175.0	2.81250	0.997 542	1.000 000
187.5	2.65625	0.996 049	1.000 000
200.0	2.50000	0.993 790	1.000 000
212.5	2.34375	0.990 455	1.000 000
225.0	2.18750	0.985 647	1.000 000
237.5	2.03125	0.978 885	1.000 000
250.0	1.87500	0.969 604	1.000 000
262.5	1.71875	0.957 170	0.999 991
275.0	1.56250	0.940 915	0.999 675
287.5	1.40625	0.920 175	0.996 208
300.0	1.25000	0.894 350	0.978 758
312.5	1.09375	0.862 968	0.927 857
325.0	0.93750	0.825 749	0.827 309
337.5	0.78125	0.782 672	0.678 435
350.0	0.62500	0.734 014	0.502 382
362.5	0.46875	0.680 376	0.330 032
375.0	0.31250	0.622 670	0.188 288
387.5	0.15625	0.562 082	0.090 635
400.0	0.00000	0.500 000	0.035 351
412.5	-0.15625	0.437 918	0.010 552
425.0	-0.31250	0.377 330	0.002 224
437.5	-0.46875	0.319 624	0.000 295
450.0	-0.62500	0.265 986	0.000 021
462.5	-0.78125	0.217 328	0.000 001
475.0	-0.93750	0.174 251	0.000 000
487.5	-1.09375	0.137 032	0.000 000
500.0	-1.25000	0.105 650	0.000 000

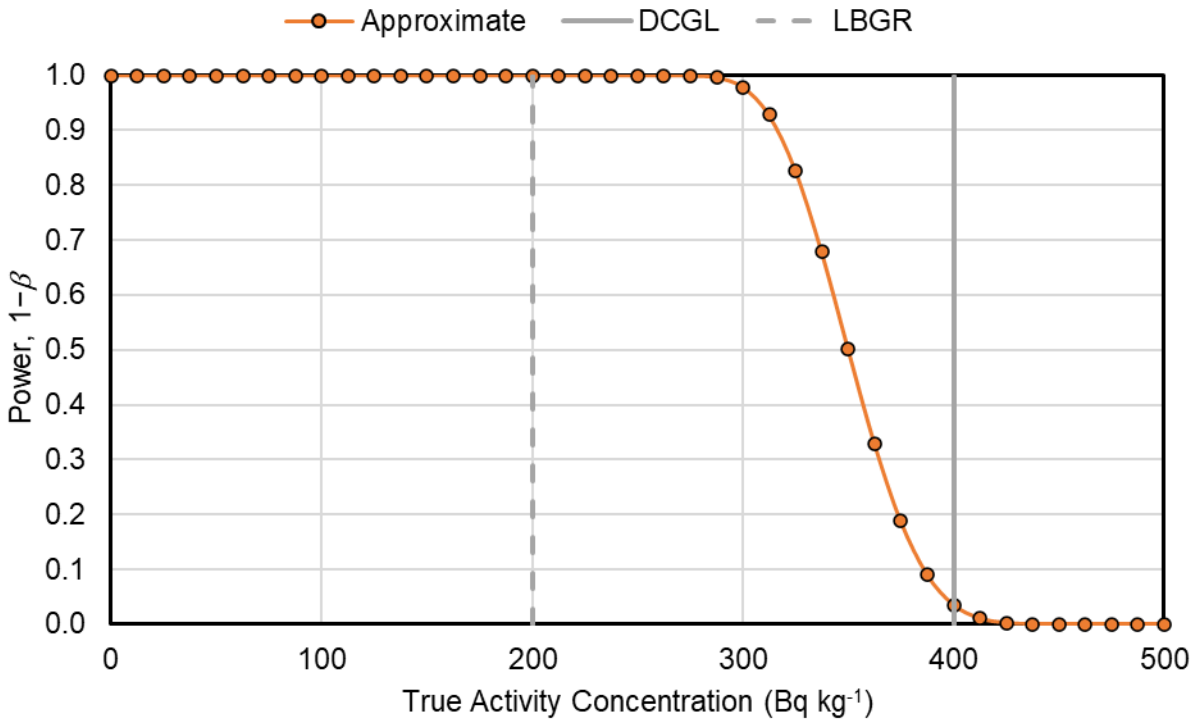

Figure M-1 Power Curve for Example M-1, Using Calculated Values Provided in Table M-1

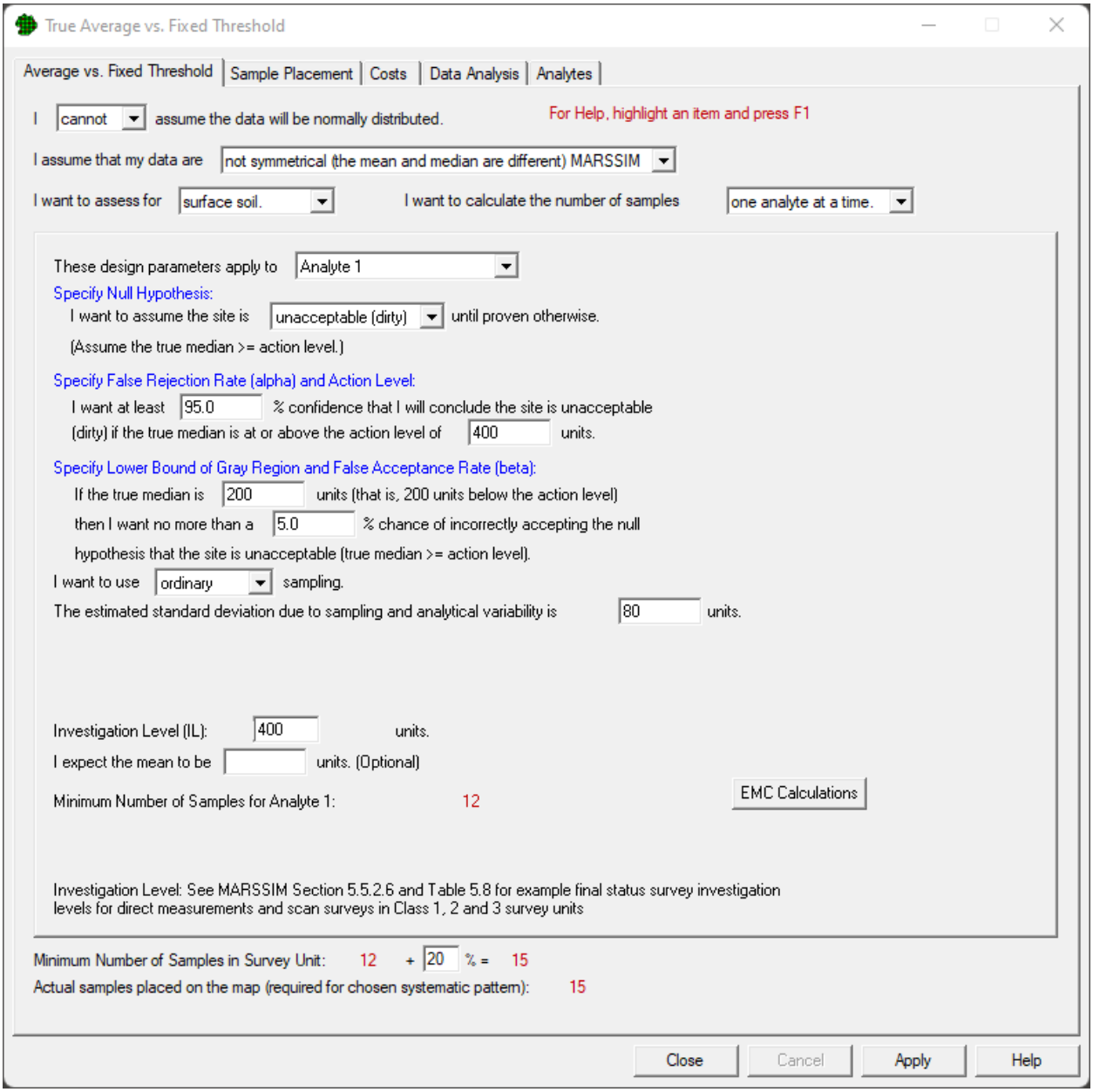

Figure M-2 Visual Sample Plan (Version 7.19) User Interface Dialog Box for Example M-1

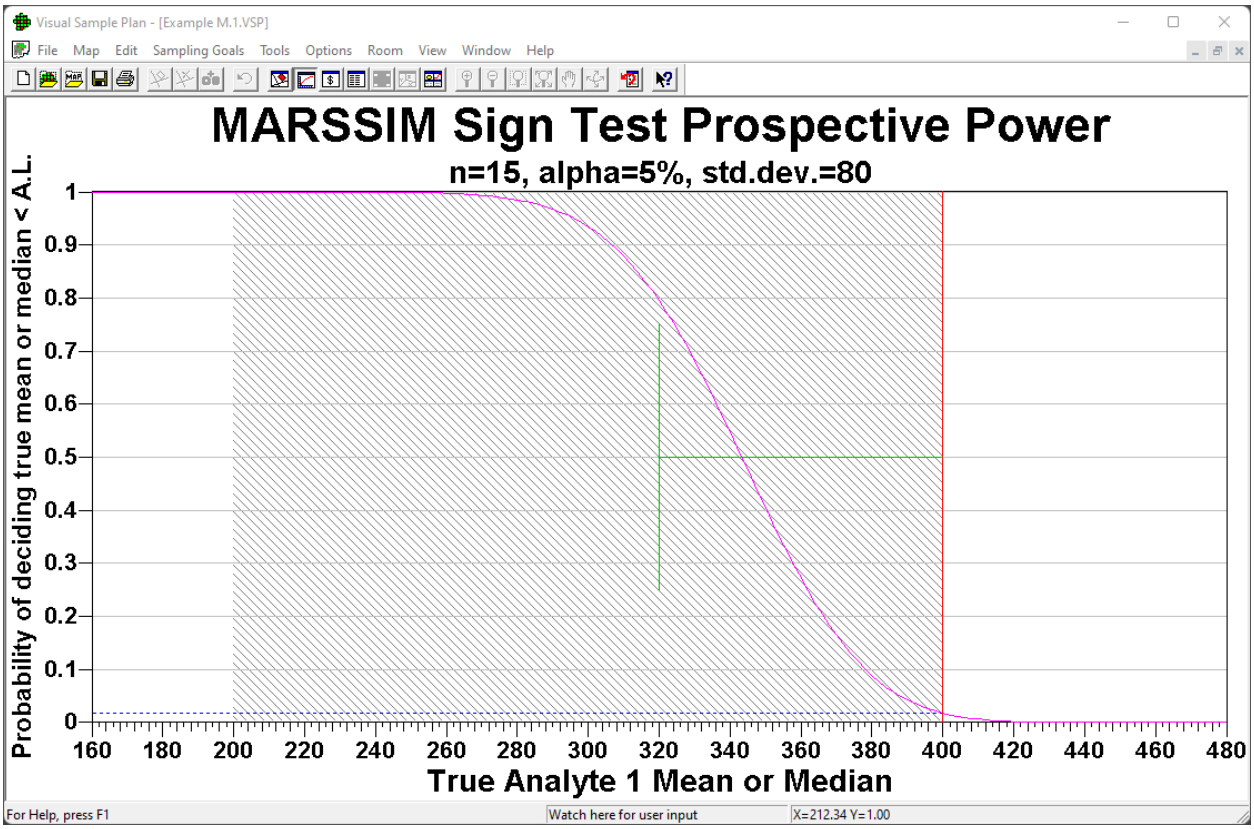

Figure M-3 Power Curve Generated by Visual Sample Plan (Version 7.19) for Example M-1

M.1.2 Sign Test under Scenario B

The following steps can be used to calculate the power of the Sign test under Scenario B:

(1) For each value of x, calculate the relative shift using the following equation:

$$\Delta/\sigma = \frac{x - \mathrm{AL}}{\sigma} \qquad \textbf{Equation M-5}$$

where:

AL = action level
x = true value of the parameter of interest
σ = variability of measurements in the survey unit, given as the standard deviation

(2) Set $N = n_s$ (the number of survey unit measurements).

(3) Look up the critical value, k, given in **Table I-4** for the appropriate values of N and α.

(4) For each value of Δ/σ, calculate $q^*(\Delta/\sigma)$ using **Equation M-2,** repeated here:

$$q^*(\Delta/\sigma) = \Phi(\Delta/\sigma)$$

where $\Phi(z)$ is the standard normal cumulative distribution function tabulated in **Table I-1**.

(5) For each value of *x*, calculate the power, $1-\beta(x)$, using one of the following two equations (MARSSIM provides two methods to estimate the power of the Sign test: an exact method, as given in **Equation M-3**, and an approximate method, as given in **Equation M-4,** both repeated here:

$$1-\beta(x) = 1-\sum_{i=0}^{k}\binom{N}{i}[q^*(\Delta/\sigma)]^i[1-q^*(\Delta/\sigma)]^{N-i}$$

$$1-\beta(x) \approx 1-\Phi\left(\frac{k-N\cdot q^*(\Delta/\sigma)}{\sqrt{N[q^*(\Delta/\sigma)][1-q^*(\Delta/\sigma)]}}\right)$$

While **Example M-1** applies both methods for purposes of illustration, it is usually sufficient to calculate the power using one or the other, but not both.

Note that if Δ/σ is large, $q^*(\Delta/\sigma)$ approaches 1, and the power also approaches 1. This calculation can be performed for other values of Δ to construct a power curve for the test. These calculations can also be performed using the sample standard deviation of the actual measurement data, *s*, to construct a retrospective power curve for the test. This is an important step when the null hypothesis is not rejected under Scenario B, because it demonstrates whether the Data Quality Objectives (DQOs) have been met.

For a retrospective power analysis, if $\beta(x)$ at *x* = DL (discrimination limit) is less than the Type II error specified during the survey design process, the survey has sufficient power to meet the DQOs. The retrospective power curve for the Sign test can be constructed using the actual number of concentration measurements obtained, N. The power as a function of Δ/σ is calculated, where σ is approximated by the observed sample standard deviation. **Example M-2** shows the calculation of the power of the Sign test under Scenario B.

Example M-2: Using Scenario B, the AL is zero, the DL is 100 Bq kg^{-1}, and the estimated standard deviation is 50 Bq kg^{-1}. The Type I error at the AL and the Type II error at the DL are both set at 0.05. The number of samples required for the Sign test is 15 ($N = 15$).

The relative shift, Δ/σ, at the DL of 100 Bq kg^{-1} is as follows:

$$\Delta/\sigma = \frac{\text{DL} - \text{AL}}{\sigma} = \frac{100 \text{ Bq kg}^{-1} - 0 \text{ Bq kg}^{-1}}{50 \text{ Bq kg}^{-1}} = 2.0$$

For $N = 15$ and $\alpha = 0.05$, the critical value is 11 ($k = 11$). The value of $q^*(\Delta/\sigma)$ at the LBGR is as follows:

$$q^*(\Delta/\sigma) = \Phi(\Delta/\sigma) = q^*(2.0) = \Phi(2.0) = 0.977\,250$$

The exact power at the DL is as follows:

$$\begin{aligned}
1 - \beta &= 1 - \sum_{i=0}^{k} \binom{N}{i} [q^*(\Delta/\sigma)]^i [1 - q^*(\Delta/\sigma)]^{N-i} \\
&= 1 - \sum_{i=0}^{k} \binom{15}{i} [q^*(2.0)]^i [1 - q^*(2.0)]^{15-i} \\
&= 1 - \sum_{i=0}^{11} \binom{15}{i} [0.977\,250]^i [1 - 0.977\,250]^{15-i} \\
&= 1 - \left(\frac{15!}{15!\,0!}[0.977\,250]^0[1 - 0.977\,250]^{15} + \cdots + \frac{15!}{11!\,4!}[0.977\,250]^{11}[1 - 0.977\,250]^4\right) \\
&= 0.999\,701
\end{aligned}$$

The approximate power at the DL is as follows:

$$\begin{aligned}
1 - \beta &\approx 1 - \Phi\left(\frac{k - N \cdot q^*(\Delta/\sigma)}{\sqrt{N[q^*(\Delta/\sigma)][1 - q^*(\Delta/\sigma)]}}\right) \\
&\approx 1 - \Phi\left(\frac{11 - 15 \cdot q^*(2.0)}{\sqrt{15[q^*(2.0)][1 - q^*(2.0)]}}\right) \\
&\approx 1 - \Phi\left(\frac{11 - 15 \cdot 0.993\,790}{\sqrt{15[0.977\,250][1 - 0.977\,250]}}\right) \\
&\approx 1.000\,000
\end{aligned}$$

Table M-2 and **Figure M-4** show the results for the power curve calculation. **Figure M-5** and **Figure M-6** show the Visual Sample Plan (Version 7.19) user interface dialog box and power curve, respectively, for **Example M-2**.

Table M-2 Calculations for Example M-2 of Power Curve for the Sign Test under Scenario B for the Exact Value and Approximate Value, Using Equation M-3 and Equation M-4

True Activity Concentration [Bq kg^{-1}]	Δ/σ	$q^*(\Delta/\sigma)$	$1-\beta$ Approximate
0.0	0.00000	0.500 000	0.035 351
5.0	0.10000	0.539 828	0.066 334
10.0	0.20000	0.579 260	0.113 383
15.0	0.30000	0.617 911	0.178 786
20.0	0.40000	0.655 422	0.262 729
25.0	0.50000	0.691 462	0.362 760
30.0	0.60000	0.725 747	0.473 745
35.0	0.70000	0.758 036	0.588 386
40.0	0.80000	0.788 145	0.698 297
45.0	0.90000	0.815 940	0.795 474
50.0	1.00000	0.841 345	0.873 893
55.0	1.10000	0.864 334	0.930 782
60.0	1.20000	0.884 930	0.967 111
65.0	1.30000	0.903 200	0.986 958
70.0	1.40000	0.919 243	0.995 887
75.0	1.50000	0.933 193	0.999 033
80.0	1.60000	0.945 201	0.999 844
85.0	1.70000	0.955 435	0.999 985
90.0	1.80000	0.964 070	0.999 999
95.0	1.90000	0.971 283	1.000 000
100.0	2.00000	0.977 250	1.000 000
105.0	2.10000	0.982 136	1.000 000
110.0	2.20000	0.986 097	1.000 000
115.0	2.30000	0.989 276	1.000 000
120.0	2.40000	0.991 802	1.000 000
125.0	2.50000	0.993 790	1.000 000
130.0	2.60000	0.995 339	1.000 000
135.0	2.70000	0.996 533	1.000 000
140.0	2.80000	0.997 445	1.000 000
145.0	2.90000	0.998 134	1.000 000
150.0	3.00000	0.998 650	1.000 000
155.0	3.10000	0.999 032	1.000 000
160.0	3.20000	0.999 313	1.000 000
165.0	3.30000	0.999 517	1.000 000
170.0	3.40000	0.999 663	1.000 000
175.0	3.50000	0.999 767	1.000 000
180.0	3.60000	0.999 841	1.000 000
185.0	3.70000	0.999 892	1.000 000
190.0	3.80000	0.999 928	1.000 000
195.0	3.90000	0.999 952	1.000 000
200.0	4.00000	0.999 968	1.000 000

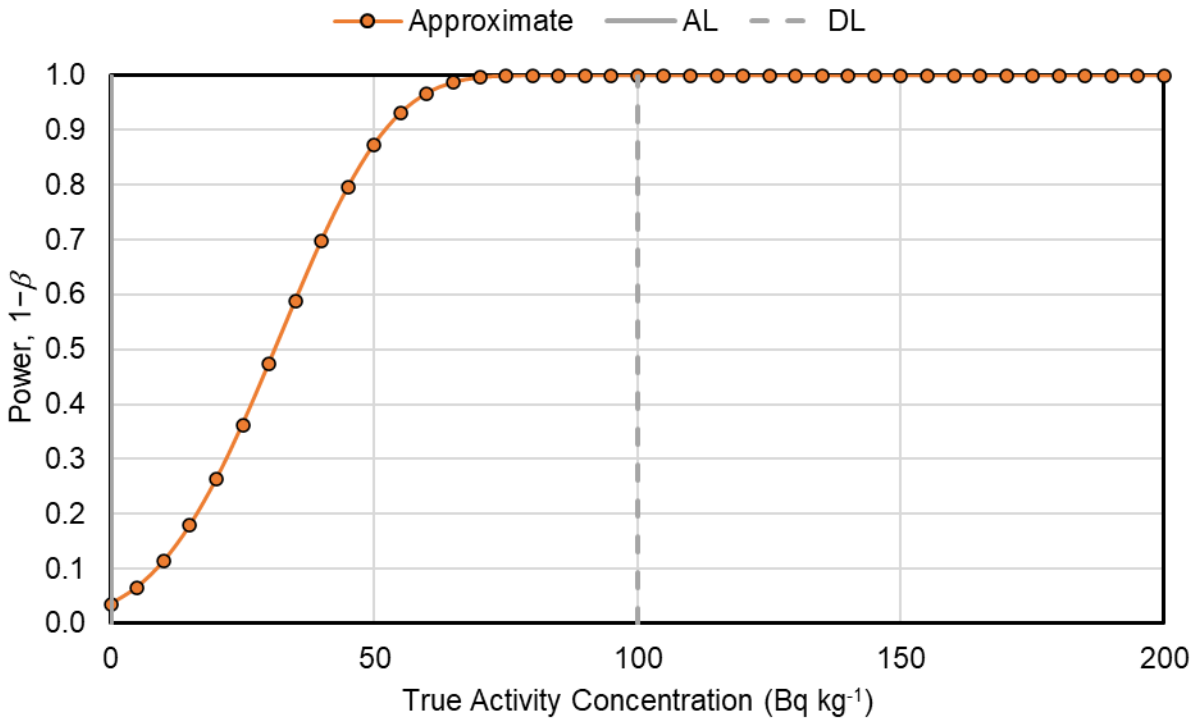

Figure M-4 Power Curves for Example M-2, Using Calculated Values Provided in Table M-2

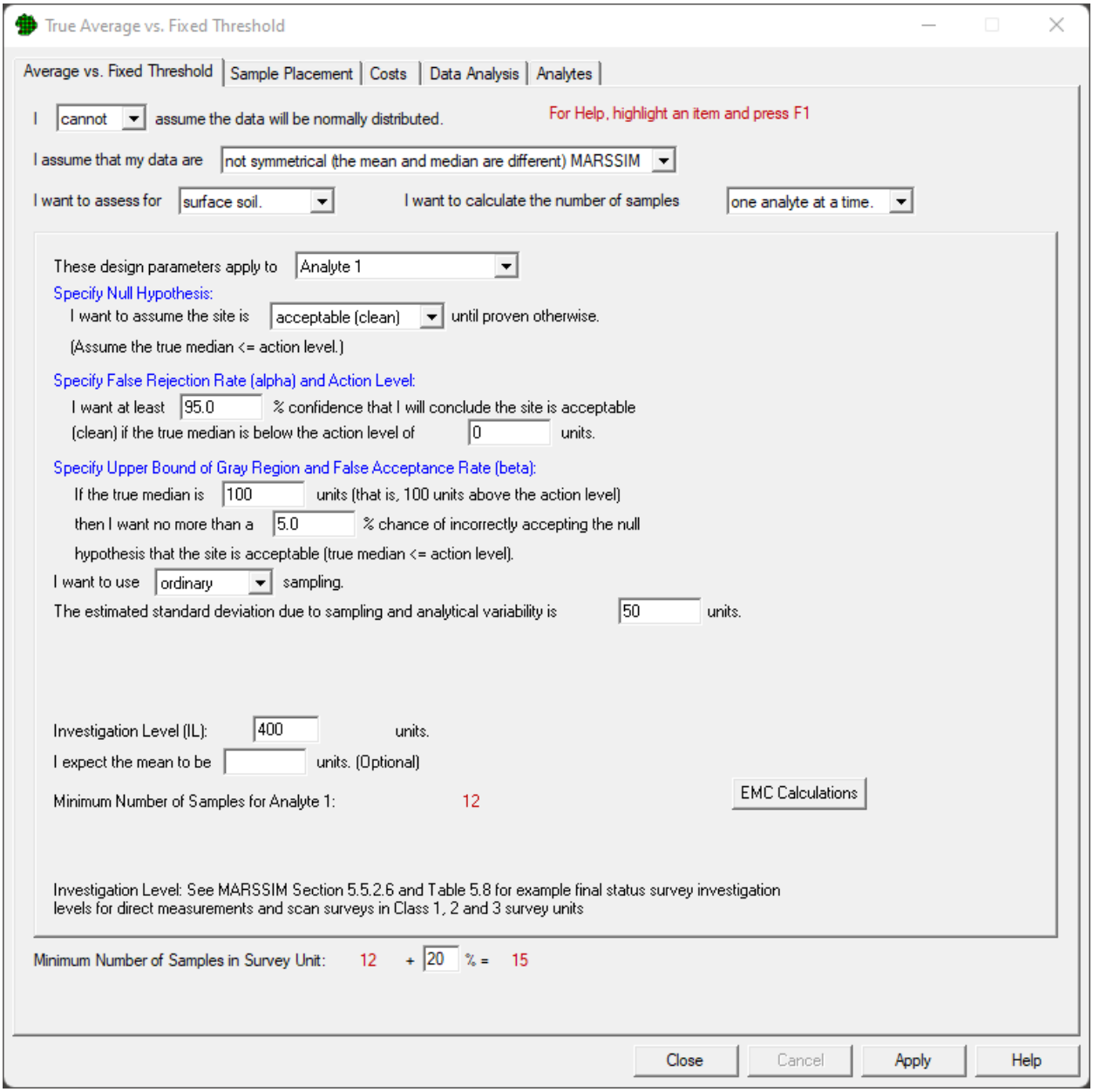

Figure M-5 Visual Sample Plan (Version 7.19) User Interface Dialog Box for Example M-2

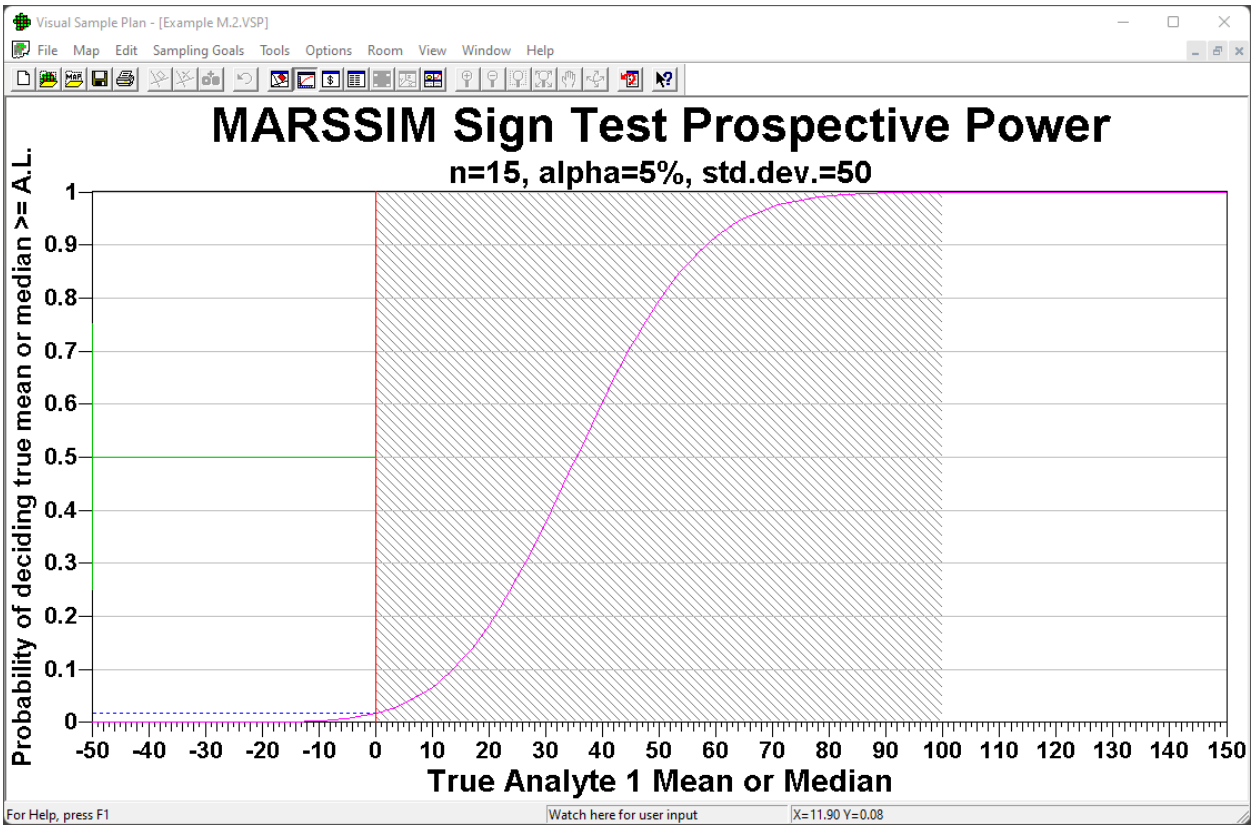

Figure M-6 Power Curve Generated by Visual Sample Plan (Version 7.19) for Example M-2

M.2 Wilcoxon Rank Sum Test

If the radionuclide is part of the natural background, or radionuclide-specific measurements will not be made, MARSSIM recommends use of the WRS test.

M.2.1 Wilcoxon Rank Sum Test under Scenario A

The following steps can be used to calculate the power of the WRS test under Scenario A:

(1) For each value of *x*, calculate the relative shift using **Equation M-1**:

$$\Delta/\sigma = \mathrm{DCGL_W} - x\sigma$$

where:

$\mathrm{DCGL_W}$ = wide-area dose concentration guideline level

x = true value of the parameter of interest

σ = variability of measurements in the survey unit, given as the standard deviation

(2) Set m = n_r (the number of reference area measurements) and n = n_s (the number of survey unit measurements).

(3) Look up the critical value, W_C, given in **Table I-6** for the appropriate values of n, m, and α.

(4) For each value of Δ/σ, look up the value of $P_r(\Delta/\sigma)$ and $p_2(\Delta/\sigma)$ in **Table M-3**.[1]

(5) For each value of Δ/σ, calculate the mean,[2] $E(W_{MW})$, and variance, $Var(W_{MW})$, of the Mann-Whitney form of the WRS test statistic, W_{MW}, using the following equations:

$$E(W_{MW}) = mnP_r(\Delta/\sigma) \qquad \textbf{Equation M-6}$$

$$Var(W_{MW}) = mn[P_r(\Delta/\sigma)][1 - P_r(\Delta/\sigma)] + mn(n + m - 2)\,(p_2(\Delta/\sigma) - [P_r(\Delta/\sigma)]^2) \qquad \textbf{Equation M-7}$$

(6) For each value of x, calculate the power, $1-\beta(x)$, using the following equation:

$$1 - \beta(x) \approx 1 - \Phi\left(\frac{W_c - (m^2+m+1)/2 - E(W_{MW})}{\sqrt{Var(W_{MW})}}\right) \qquad \textbf{Equation M-8}$$

where $\Phi(z)$ is the standard normal cumulative distribution function tabulated in **Table I-1**.

Example M-3 shows the calculation of the power of the WRS test under Scenario A.

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[1] According to NUREG-1505, Revision 1, "A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys: Interim Draft Report for Use and Comment," issued June 1998 (NRC 1998a), P_r is the estimated probability that a random measurement from the survey unit exceeds a random measurement from the reference area by less than the $DCGL_W$ when the survey unit median is at the LBGR above background (NUREG-1505, page 9-9), and p_2 is the probability that two random measurements from the survey unit will each exceed a single random measurement from the reference area by less than the $DCGL_W$ (NUREG-1505, page 10-9).

[2] In MARSSIM, "average" and "mean" both refer to the arithmetic mean.

Table M-3 Values of $P_r(\Delta/\sigma)$ and $p_2(\Delta/\sigma)$ for Computing the Mean and Variance of W_{MW}

Δ/σ	$P_r(\Delta/\sigma)$	$p_2(\Delta/\sigma)$	Δ/σ	$P_r(\Delta/\sigma)$	$p_2(\Delta/\sigma)$
-6.0	1.11×10^{-5}	1.16×10^{-7}	**0.7**	0.689 691	0.544 073
-5.0	0.000 204	6.14×10^{-6}	**0.8**	0.714 196	0.574 469
-4.0	0.002 339	0.000 174	**0.9**	0.737 741	0.604 402
-3.5	0.006 664	0.000 738	**1.0**	0.760 250	0.633 702
-3.0	0.016 947	0.002 690	**1.1**	0.781 662	0.662 216
-2.5	0.038 550	0.008 465	**1.2**	0.801 928	0.689 800
-2.0	0.078 650	0.023 066	**1.3**	0.821 015	0.716 331
-1.9	0.089 555	0.027 714	**1.4**	0.838 901	0.741 698
-1.8	0.101 546	0.033 114	**1.5**	0.855 578	0.765 812
-1.7	0.114 666	0.039 348	**1.6**	0.871 050	0.788 602
-1.6	0.128 950	0.046 501	**1.7**	0.885 334	0.810 016
-1.5	0.144 422	0.054 656	**1.8**	0.898 454	0.830 022
-1.4	0.161 099	0.063 897	**1.9**	0.910 445	0.848 605
-1.3	0.178 985	0.074 301	**2.0**	0.921 350	0.865 767
-1.2	0.198 072	0.085 944	**2.1**	0.931 218	0.881 527
-1.1	0.218 338	0.098 892	**2.2**	0.940 103	0.895 917
-1.0	0.239 750	0.113 202	**2.3**	0.948 062	0.908 982
-0.9	0.262 259	0.128 920	**2.4**	0.955 157	0.920 777
-0.8	0.285 804	0.146 077	**2.5**	0.961 450	0.931 365
-0.7	0.310 309	0.164 691	**2.6**	0.967 004	0.940 817
-0.6	0.335 687	0.184 760	**2.7**	0.971 881	0.949 208
-0.5	0.361 837	0.206 266	**2.8**	0.976 143	0.956 616
-0.4	0.388 649	0.229 172	**2.9**	0.979 848	0.963 118
-0.3	0.416 002	0.253 419	**3.0**	0.983 053	0.968 795
-0.2	0.443 769	0.278 930	**3.1**	0.985 811	0.973 725
-0.1	0.471 814	0.305 606	**3.2**	0.988 174	0.977 981
0.0	0.500 000	0.333 333	**3.3**	0.990 188	0.981 636
0.1	0.528 186	0.361 978	**3.4**	0.991 895	0.984 758
0.2	0.556 231	0.391 392	**3.5**	0.993 336	0.987 410
0.3	0.583 998	0.421 415	**4.0**	0.997 661	0.995 497
0.4	0.611 351	0.451 875	**5.0**	0.999 796	0.999 599
0.5	0.638 163	0.482 593	**6.0**	0.999 989	0.999 978
0.6	0.664 313	0.513 387			

Example M-3: Using Scenario A, the DCGL is 8,000 Bq per square meter (m^{-2}), the LBGR is 4,000 Bq m^{-2}, and the estimated standard deviation is 1,600 Bq m^{-2}. The Type I error at the DCGL and Type II error at the LBGR are both set at 0.05. The number of samples required for the WRS test in the survey unit and the reference area is 11 ($N/2 = 11$).

The relative shift, Δ/σ, at the LBGR of 4,000 Bq m^{-2} is as follows:

$$\Delta/\sigma = \text{DCGL} - \text{LBGR}\sigma = \frac{8{,}000 \text{ Bq m}^{-2} - 4{,}000 \text{ Bq m}^{-2}}{1{,}600 \text{ Bq kg}^{-1}} = 2.5$$

For $n_r = 11$ and $n_s = 11$—

$$m = \mathrm{n_r} = 11$$

$$n = \mathrm{n_s} = 11$$

For $m = 11$, $n = 11$, and $\alpha = 0.05$, the critical value is 152 ($W_C = 152$). For $\Delta/\sigma = 2.5$—

$$P_r(\Delta/\sigma) = P_r(2.5) = 0.961\,450$$

$$p_2(\Delta/\sigma) = p_2(2.5) = 0.931\,365$$

The mean, $\mathrm{E}(W_{\mathrm{MW}})$, of the Mann-Whitney form of the WRS test statistic, W_{MW}, is as follows:

$$\mathrm{E}(W_{\mathrm{MW}}) = mnP_r(\Delta/\sigma) = 11{\cdot}11{\cdot}P_r(2.5) = 11{\cdot}11{\cdot}0.961\,450 = 116.34$$

The variance, $\mathrm{Var}(W_{\mathrm{MW}})$, of the Mann-Whitney form of the WRS test statistic, W_{MW}, is as follows:

$$\begin{aligned}\mathrm{Var}(W_{\mathrm{MW}}) &= mn[P_r(\Delta/\sigma)][1 - P_r(\Delta/\sigma)] + mn(n + m - 2)(p_2(\Delta/\sigma) - [P_r(\Delta/\sigma)]^2) \\ &= 11{\cdot}11{\cdot}[P_r(2.5)][1 - P_r(2.5)] + 11{\cdot}11{\cdot}(11 + 11 - 2)(p_2(2.5) - [P_r(2.5)]^2) \\ &= 11{\cdot}11{\cdot}[0.961\,450][1 - 0.961\,450] \\ &\quad + 11{\cdot}11{\cdot}(11 + 11 - 2)(0.931\,365 - (0.961\,450)^2) \\ &= 21.37\end{aligned}$$

The approximate power at the LBGR is as follows:

$$\begin{aligned}1 - \beta &\approx 1 - \Phi\left(\frac{W_c - (m^2 + m + 1)/2 - \mathrm{E}(W_{\mathrm{MW}})}{\sqrt{\mathrm{Var}(W_{\mathrm{MW}})}}\right) \\ &\approx 1 - \Phi\left(\frac{152 - (11^2 + 11 + 1)/2 - 116.34}{\sqrt{21.37}}\right) \\ &\approx 1 - \Phi(-6.671) \\ &\approx 1.000\,000\end{aligned}$$

Table M-4 and **Figure M-7** show the results for the power curve calculation. **Figure M-8** and **Figure M-9** show the Visual Sample Plan (Version 7.19) user interface dialog box and power curve, respectively, for **Example M-3**.

Table M-4 Calculations for Example M-3 of the Power Curve for the WRS Test under Scenario A, Using Equation M-8

True Activity Concentration [Bq kg^{-1}]	Δ/σ	$P_r(\Delta/\sigma)$	$p_2(\Delta/\sigma)$	E(W_{MW})	Var(W_{MW})	$1-\beta$
2,400	3.5	0.993 336	0.987 410	120.19	2.48	1.000 000
2,560	3.4	0.991 895	0.984 758	120.02	3.16	1.000 000
2,720	3.3	0.990 188	0.981 636	119.81	3.99	1.000 000
2,880	3.2	0.988 174	0.977 981	119.57	5.03	1.000 000
3,040	3.1	0.985 811	0.973 725	119.28	6.29	1.000 000
3,200	3.0	0.983 053	0.968 795	118.95	7.83	1.000 000
3,360	2.9	0.979 848	0.963 118	118.56	9.69	1.000 000
3,520	2.8	0.976 143	0.956 616	118.11	11.92	1.000 000
3,680	2.7	0.971 881	0.949 208	117.60	14.57	1.000 000
3,840	2.6	0.967 004	0.940 817	117.01	17.70	1.000 000
4,000	2.5	0.961 450	0.931 365	116.34	21.37	1.000 000
4,160	2.4	0.955 157	0.920 777	115.57	25.64	1.000 000
4,320	2.3	0.948 062	0.908 982	114.72	30.55	1.000 000
4,480	2.2	0.940 103	0.895 917	113.75	36.15	0.999 999
4,640	2.1	0.931 218	0.881 527	112.68	42.50	0.999 985
4,800	2.0	0.921 350	0.865 767	111.48	49.62	0.999 887
4,960	1.9	0.910 445	0.848 605	110.16	57.53	0.999 427
5,120	1.8	0.898 454	0.830 022	108.71	66.22	0.997 831
5,280	1.7	0.885 334	0.810 016	107.13	75.69	0.993 536
5,440	1.6	0.871 050	0.788 602	105.40	85.89	0.984 103
5,600	1.5	0.855 578	0.765 812	103.52	96.74	0.966 568
5,760	1.4	0.838 901	0.741 698	101.51	108.18	0.938 101
5,920	1.3	0.821 015	0.716 331	99.34	120.06	0.896 766
6,080	1.2	0.801 928	0.689 800	97.03	132.26	0.842 034
6,240	1.1	0.781 662	0.662 216	94.58	144.60	0.774 928
6,400	1.0	0.760 250	0.633 702	91.99	156.90	0.697 820
6,560	0.9	0.737 741	0.604 402	89.27	168.95	0.614 010
6,720	0.8	0.714 196	0.574 469	86.42	180.53	0.527 227
6,880	0.7	0.689 691	0.544 073	83.45	191.42	0.441 179
7,040	0.6	0.664 313	0.513 387	80.38	201.41	0.359 184
7,200	0.5	0.638 163	0.482 593	77.22	210.27	0.283 942
7,360	0.4	0.611 351	0.451 875	73.97	217.81	0.217 398
7,520	0.3	0.583 998	0.421 415	70.66	223.87	0.160 703
7,680	0.2	0.556 231	0.391 392	67.30	228.31	0.114 245
7,840	0.1	0.528 186	0.361 978	63.91	231.01	0.077 737
8,000	0.0	0.500 000	0.333 333	60.50	231.92	0.050 334
8,160	-0.1	0.471 814	0.305 606	57.09	231.01	0.030 795
8,320	-0.2	0.443 769	0.278 930	53.70	228.31	0.017 652
8,480	-0.3	0.416 002	0.253 419	50.34	223.87	0.009 383
8,640	-0.4	0.388 649	0.229 172	47.03	217.81	0.004 568
8,800	-0.5	0.361 837	0.206 266	43.78	210.26	0.002 007
8,960	-0.6	0.335 687	0.184 760	40.62	201.40	0.000 782
9,120	-0.7	0.310 309	0.164 691	37.55	191.42	0.000 264
9,280	-0.8	0.285 804	0.146 077	34.58	180.53	0.000 075
9,440	-0.9	0.262 259	0.128 920	31.73	168.95	0.000 018
9,600	-1.0	0.239 750	0.113 202	29.01	156.90	0.000 003

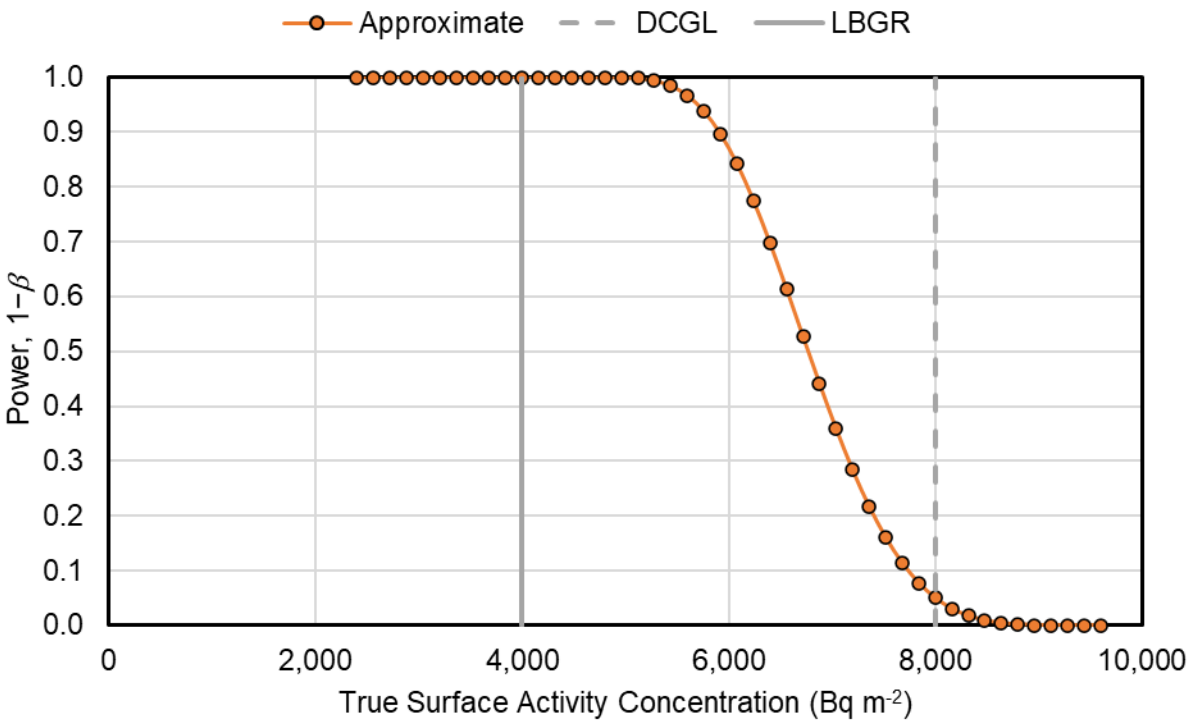

Figure M-7 Power Curve for Example M-3, Using Calculated Values Provided in Table M-4

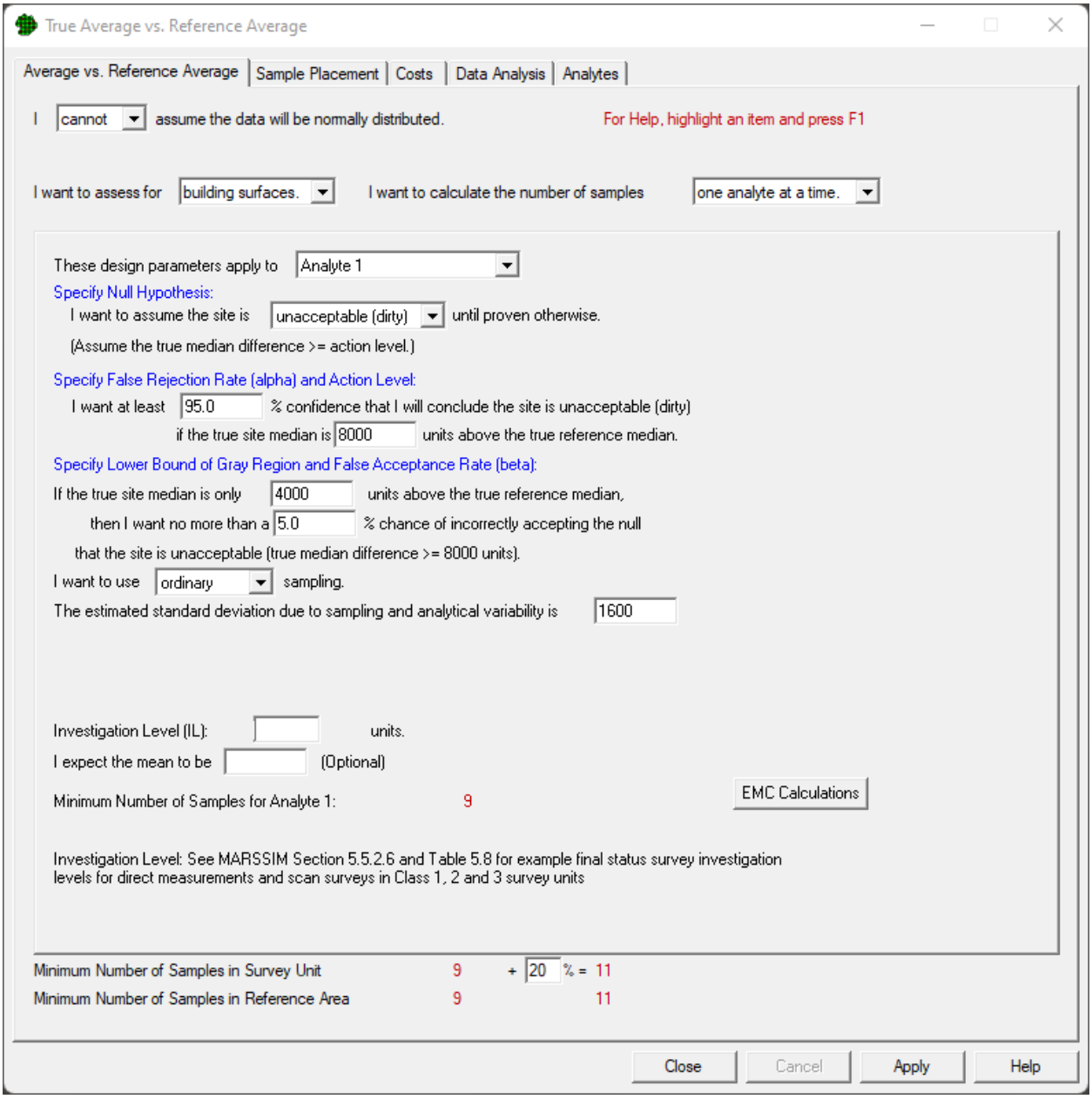

Figure M-8 Visual Sample Plan (Version 7.19) User Interface Dialog Box for Example M-3

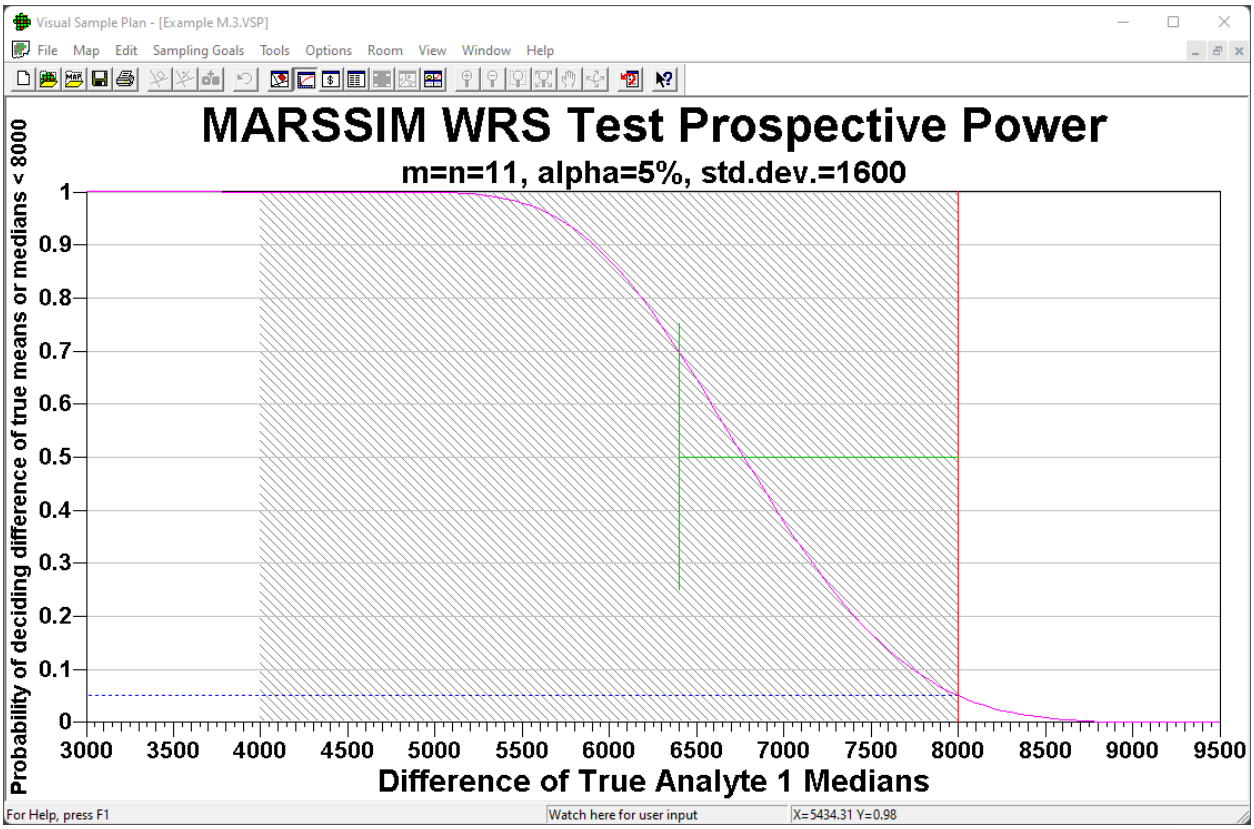

Figure M-9 Power Curve Generated by Visual Sample Plan (Version 7.19) for Example M-3

M.2.2 Wilcoxon Rank Sum Test under Scenario B

The following steps can be used to calculate the power of the WRS test under Scenario B:

(1) For each value of *x*, calculate the relative shift using **Equation M-5,** repeated here:

$$\Delta/\sigma = \frac{x - \mathrm{AL}}{\sigma}$$

where:

AL = action level

x = true value of the parameter of interest

σ = variability of measurements in the survey unit, given as the standard deviation

(2) Set *m* = n_s (the number of survey unit measurements) and *n* = n_r (the number of reference area measurements).

(3) Look up the critical value, W_C, given in **Table I-5** for the appropriate values of *n*, *m*, and α.

(4) For each value of Δ/σ, look up the value of $P_r(\Delta/\sigma)$ and $p_2(\Delta/\sigma)$ in **Table M-3**.

(5) For each value of Δ/σ, calculate the mean, $E(W_{MW})$, and variance, $Var(W_{MW})$, of the Mann-Whitney form of the WRS test statistic, W_{MW}, using **Equation M-6** and **Equation M-7,** repeated here:

$$E(W_{MW}) = mnP_r(\Delta/\sigma)$$

$$Var(W_{MW}) = mn[P_r(\Delta/\sigma)][1 - P_r(\Delta/\sigma)] + mn(n + m - 2)(p_2(\Delta/\sigma) - [P_r(\Delta/\sigma)]^2)$$

(6) For each value of *x*, calculate the power, $1-\beta(x)$, using **Equation M-8,** repeated here:

$$1 - \beta(x) \approx 1 - \Phi\left(\frac{W_c - (m^2 + m + 1)/2 - E(W_{MW})}{\sqrt{Var(W_{MW})}}\right)$$

where $\Phi(z)$ is the standard normal cumulative distribution function tabulated in **Table I-1**.

The power calculated in **Equation M-8** is an approximation, but the results are generally accurate enough to be used to determine whether the sample design achieves the DQOs. The retrospective power curve for the WRS test can be constructed using the actual number of concentration measurements obtained, N. The power as a function of Δ/σ is calculated, where σ is approximated by the observed sample standard deviation, *s*. **Example M-4** shows the calculation of the power of the WRS test under Scenario B.

Example M-4: Using Scenario B, the AL is 4,000 Bq m^{-2}, the DL is 8,000 Bq m^{-2}, and the estimated standard deviation is 1,600 Bq m^{-2}. The Type I error at the AL and Type II error at the DL are both set at 0.05. The number of samples required for the WRS test in the survey unit and the reference area is 11 ($N/2 = 11$).

The relative shift, Δ/σ, at the DL of 8,000 Bq m^{-2} is as follows:

$$\Delta/\sigma = \frac{\text{DL} - \text{AL}}{\sigma} = \frac{8{,}000 \text{ Bq m}^{-2} - 4{,}000 \text{ Bq m}^{-2}}{1{,}600 \text{ Bq kg}^{-1}} = 2.5$$

For $n_r = 11$ and $n_s = 11$—

$$m = \text{n}_\text{r} = 11$$

$$n = \text{n}_\text{s} = 11$$

For $m = 11$, $n = 11$, and $\alpha = 0.025$, the critical value is 156 ($W_\text{C} = 156$). For $\Delta/\sigma = 2.5$—

$$P_r(\Delta/\sigma) = P_r(2.5) = 0.961\,450$$
$$p_2(\Delta/\sigma) = p_2(2.5) = 0.931\,365$$

The mean, $\text{E}(W_\text{MW})$, of the Mann-Whitney form of the WRS test statistic, W_MW, is as follows:

$$\text{E}(W_\text{MW}) = mnP_r(\Delta/\sigma) = 11{\cdot}11{\cdot}P_r(2.5) = 11{\cdot}11{\cdot}0.961\,450 = 116.34$$

The variance, $\text{Var}(W_\text{MW})$, of the Mann-Whitney form of the WRS test statistic, W_MW, is as follows:

$$\begin{aligned}\text{Var}(W_\text{MW}) &= mn[P_r(\Delta/\sigma)][1 - P_r(\Delta/\sigma)] + mn(n + m - 2)(p_2(\Delta/\sigma) - [P_r(\Delta/\sigma)]^2) \\ &= 11{\cdot}11{\cdot}[P_r(2.5)][1 - P_r(2.5)] + 11{\cdot}11{\cdot}(11 + 11 - 2)(p_2(2.5) - [P_r(2.5)]^2) \\ &= 11{\cdot}11{\cdot}[0.961\,450][1 - 0.961\,450] \\ &\quad + 11{\cdot}11{\cdot}(11 + 11 - 2)(0.931\,365 - (0.961\,450)^2) \\ &= 21.37\end{aligned}$$

The approximate power at the DL is as follows:

$$\begin{aligned}1 - \beta &\approx 1 - \Phi\left(\frac{W_c - (m^2 + m + 1)/2 - \text{E}(W_\text{MW})}{\sqrt{\text{Var}(W_\text{MW})}}\right) \\ &\approx 1 - \Phi\left(\frac{156 - (11^2 + 11 + 1)/2 - 116.34}{\sqrt{21.37}}\right) \\ &\approx 1 - \Phi(-5.806) \\ &\approx 1.000\,000\end{aligned}$$

Table M-5 and **Figure M-10** show the results for the power curve calculation. **Figure M-11** and **Figure M-12** show the Visual Sample Plan (Version 7.19) user interface dialog box and power curve, respectively, for **Example M-4**.

Table M-5 Calculations for Example M-4 of the Power Curve for the WRS Test under Scenario B, Using Equation M-8

True Activity Concentration [Bq kg^{-1}]	Δ/σ	$P_r(\Delta/\sigma)$	$p_2(\Delta/\sigma)$	E(W_{MW})	Var(W_{MW})	$1-\beta$
2,400	-1.0	0.239 750	0.113 202	29.01	156.90	0.000 001
2,560	-0.9	0.262 259	0.128 920	31.73	168.95	0.000 004
2,720	-0.8	0.285 804	0.146 077	34.58	180.53	0.000 022
2,880	-0.7	0.310 309	0.164 691	37.55	191.42	0.000 087
3,040	-0.6	0.335 687	0.184 760	40.62	201.40	0.000 286
3,200	-0.5	0.361 837	0.206 266	43.78	210.26	0.000 808
3,360	-0.4	0.388 649	0.229 172	47.03	217.81	0.002 002
3,520	-0.3	0.416 002	0.253 419	50.34	223.87	0.004 429
3,680	-0.2	0.443 769	0.278 930	53.70	228.31	0.008 904
3,840	-0.1	0.471 814	0.305 606	57.09	231.01	0.016 486
4,000	0.0	0.500 000	0.333 333	60.50	231.92	0.028 436
4,160	0.1	0.528 186	0.361 978	63.91	231.01	0.046 126
4,320	0.2	0.556 231	0.391 392	67.30	228.31	0.070 918
4,480	0.3	0.583 998	0.421 415	70.66	223.87	0.104 031
4,640	0.4	0.611 351	0.451 875	73.97	217.81	0.146 390
4,800	0.5	0.638 163	0.482 593	77.22	210.27	0.198 491
4,960	0.6	0.664 313	0.513 387	80.38	201.41	0.260 276
5,120	0.7	0.689 691	0.544 073	83.45	191.42	0.331 023
5,280	0.8	0.714 196	0.574 469	86.42	180.53	0.409 278
5,440	0.9	0.737 741	0.604 402	89.27	168.95	0.492 839
5,600	1.0	0.760 250	0.633 702	91.99	156.90	0.578 793
5,760	1.1	0.781 662	0.662 216	94.58	144.60	0.663 684
5,920	1.2	0.801 928	0.689 800	97.03	132.26	0.743 779
6,080	1.3	0.821 015	0.716 331	99.34	120.06	0.815 483
6,240	1.4	0.838 901	0.741 698	101.51	108.18	0.875 840
6,400	1.5	0.855 578	0.765 812	103.52	96.74	0.923 052
6,560	1.6	0.871 050	0.788 602	105.40	85.89	0.956 861
6,720	1.7	0.885 334	0.810 016	107.13	75.69	0.978 615
6,880	1.8	0.898 454	0.830 022	108.71	66.22	0.990 887
7,040	1.9	0.910 445	0.848 605	110.16	57.53	0.996 779
7,200	2.0	0.921 350	0.865 767	111.48	49.62	0.999 098
7,360	2.1	0.931 218	0.881 527	112.68	42.50	0.999 811
7,520	2.2	0.940 103	0.895 917	113.75	36.15	0.999 973
7,680	2.3	0.948 062	0.908 982	114.72	30.55	0.999 997
7,840	2.4	0.955 157	0.920 777	115.57	25.64	1.000 000
8,000	2.5	0.961 450	0.931 365	116.34	21.37	1.000 000
8,160	2.6	0.967 004	0.940 817	117.01	17.70	1.000 000
8,320	2.7	0.971 881	0.949 208	117.60	14.57	1.000 000
8,480	2.8	0.976 143	0.956 616	118.11	11.92	1.000 000
8,640	2.9	0.979 848	0.963 118	118.56	9.69	1.000 000
8,800	3.0	0.983 053	0.968 795	118.95	7.83	1.000 000
8,960	3.1	0.985 811	0.973 725	119.28	6.29	1.000 000
9,120	3.2	0.988 174	0.977 981	119.57	5.03	1.000 000
9,280	3.3	0.990 188	0.981 636	119.81	3.99	1.000 000
9,440	3.4	0.991 895	0.984 758	120.02	3.16	1.000 000
9,600	3.5	0.993 336	0.987 410	120.19	2.48	1.000 000

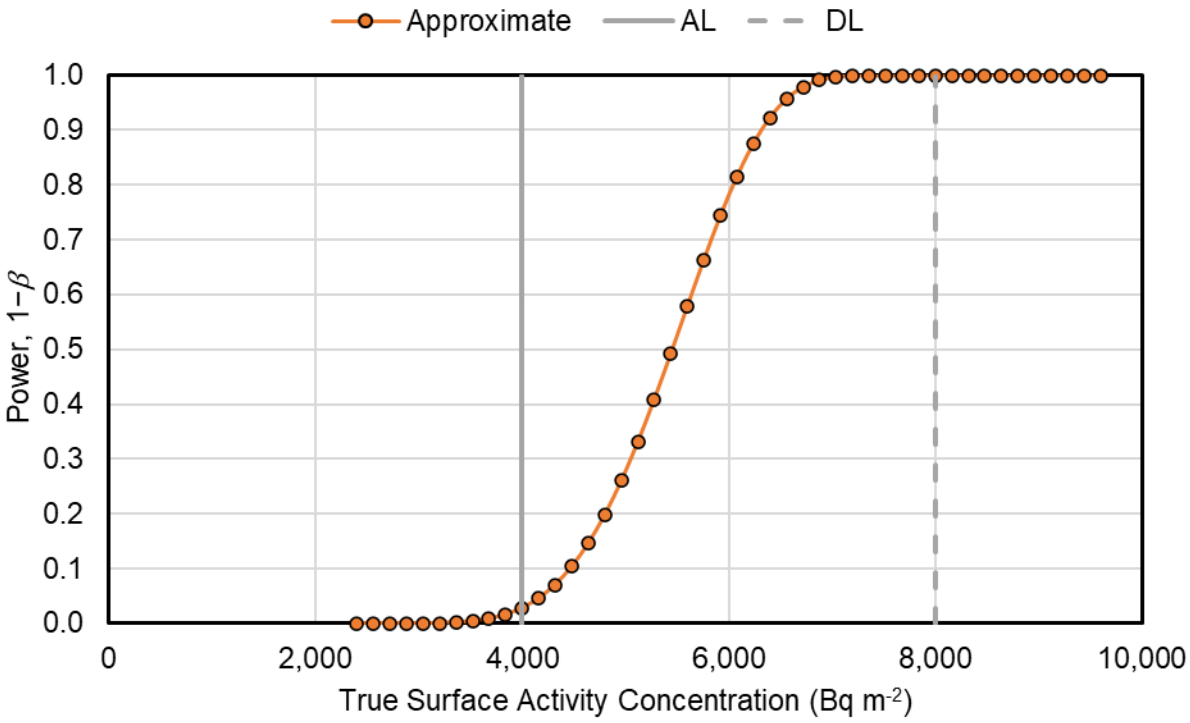

Figure M-10 Power Curves for Example M-4, Using Calculated Values Provided in Table M-5

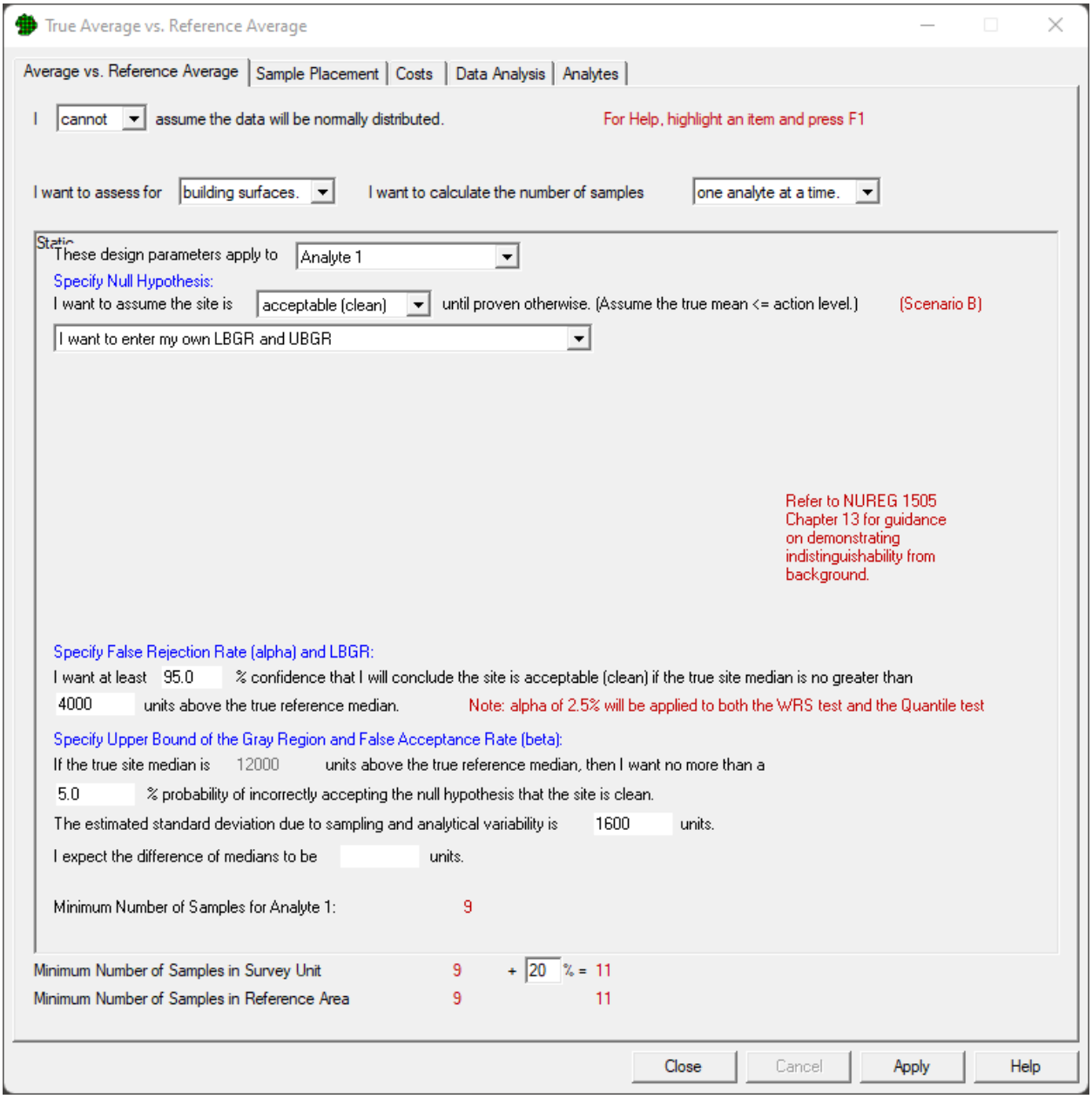

Figure M-11 Visual Sample Plan (Version 7.19) User Interface Dialog Box for Example M-4

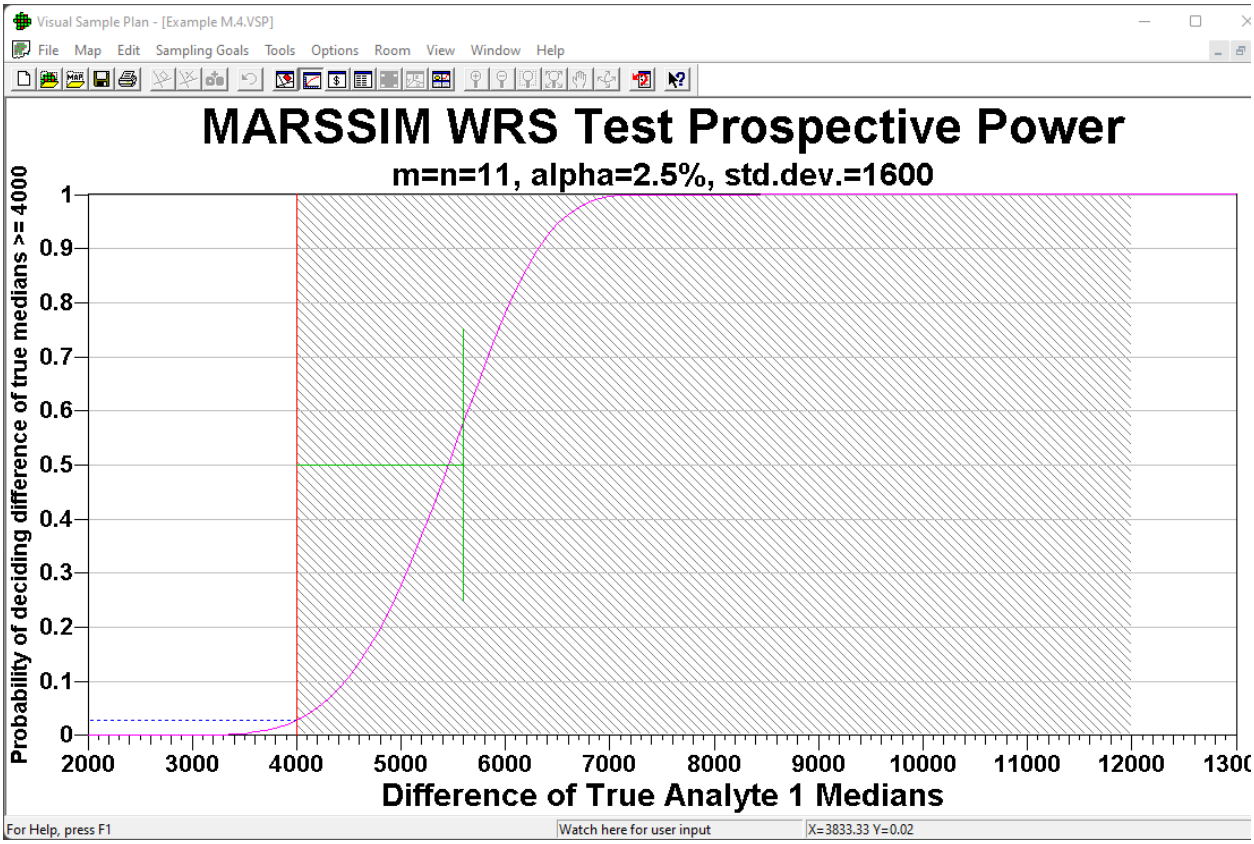

Figure M-12 Power Curve Generated by Visual Sample Plan (Version 7.19) for Example M-4

APPENDIX N
CALCULATING THE NUMBER OF SAMPLES NEEDED FOR THE WILCOXON RANK SUM AND SIGN TESTS

N.1 Introduction

This appendix explains the method used to determine the number of data points (direct measurements or samples) for the Wilcoxon Rank Sum (WRS) test and Sign test. **Tables I-2** and **I-3** in **Appendix I** also provided tabulated values of sample size based on specified error rates and expected relative shift for the Sign and WRS tests, respectively. (Refer to additional information in the rest of this appendix on relative shift.) The WRS test is used when residual radioactive material is present in the background, when measurements are not radionuclide specific, or if the net concentration of radioactive material at each location cannot be obtained. The Sign test is used when residual radioactive material is not in the background, when measurements are radionuclide specific, or if background levels are a small fraction of the derived concentration guideline level (DCGL).

N.2 The Wilcoxon Rank Sum Test

The steps required to determine the number of data points for the WRS test are described in this section. The WRS test can be used for either Scenario A or B. When Scenario B is used, the Quantile test also is required. Finally, the data must meet the requirements necessary to use the statistical tests, including required statistical power, especially for Scenario B.

N.2.1 Determine P_r

For Scenario A, the probability that a random measurement from the survey unit exceeds a random measurement from the background reference area by less than the $DCGL_W$ (i.e., the DCGL for average concentrations over a wide area) when the survey unit median is equal to the lower bound of the gray region (LBGR) above background is defined as P_r. For Scenario B, P_r is the estimated probability that the difference between a random measurement from the survey unit and a random measurement from the reference area will be greater than the LBGR (the action level) when the survey unit median is actually at the upper bound of the gray region (UBGR) or discrimination limit above the background median. **Equation N-1** uses P_r for determining the number of measurements to be performed during the survey (refer to also **Section 5.3.3**). **Table N-1** lists relative shift values and values for P_r. Using the relative shift, described in **Section 5.3,** the value of P_r can be obtained from **Table N-1.** Information on calculating individual values of P_r is available in NUREG-1505, Revision 1, "A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys: Interim Draft Report for Comment and Use," issued June 1998 (NRC 1998a). If **Table N-1** does not list the actual value of the relative shift, always select the next lower value that appears in the table. For example, $\Delta/\sigma = 1.67$ does not appear in **Table N-1.** The next lower value is 1.6, so the value of P_r would be 0.871014.

Table N-1 Values of P_r for Given Values of the Relative Shift, Δ/σ, When the Radionuclide Is Present in Background[1]

Δ/σ	P_r	Δ/σ	P_r
0.1	0.528186	2.1	0.931218
0.2	0.556231	2.2	0.940103
0.3	0.583998	2.3	0.948062
0.4	0.611351	2.4	0.955157
0.5	0.638163	2.5	0.961450
0.6	0.664313	2.6	0.967004
0.7	0.689691	2.7	0.971881
0.8	0.714196	2.8	0.976143
0.9	0.737741	2.9	0.979848
1.0	0.760250	3.0	0.983053
1.1	0.781662	3.1	0.985811
1.2	0.801928	3.2	0.988174
1.3	0.821015	3.3	0.990188
1.4	0.838901	3.4	0.991895
1.5	0.855578	3.5	0.993336
1.6	0.871050	4.0	0.997661
1.7	0.885334	5.0	0.999796
1.8	0.898454	6.0	0.999989
1.9	0.910445		
2.0	0.921350		

[1] If Δ/σ > 6.0, use P_r = 1.000000.

N.2.2 Determine Decision Error Percentiles

The next step in this process is to determine the percentiles, $Z_{1-\alpha}$ and $Z_{1-\beta}$, represented by the selected decision error levels, α and β, respectively (refer to **Table N-2**). $Z_{1-\alpha}$ and $Z_{1-\beta}$ are standard statistical values (Harnett 1975).

Table N-2 Percentiles Represented by Selected Values of α and β

α (or β)	$Z_{1-\alpha}$ (or $Z_{1-\beta}$)
0.005	2.576
0.01	2.326
0.015	2.170
0.025	1.960
0.05	1.645

α (or β)	$Z_{1-\alpha}$ (or $Z_{1-\beta}$)
0.10	1.282
0.15	1.036
0.20	0.842
0.25	0.674
0.30	0.524

N.2.3 Calculate Number of Data Points for Wilcoxon Rank Sum Test

The number of data points, *N*, to be obtained from each reference area/survey unit pair for the WRS test is next calculated using the following formula:[1]

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{3(P_r - 0.5)^2} \qquad \textbf{Equation N-1}$$

The value of *N* calculated using **Table N-1** is an approximation based on estimates of σ and P_r, so there is some uncertainty associated with this calculation. In addition, there may be some missing or unusable data from the survey. The rate of missing or unusable measurements, *R*, expected to occur in survey units or reference areas and the uncertainty associated with the calculation of *N* should[2] be accounted for during survey planning. The number of data points should be increased by 20 percent, and rounded up, over the values calculated using **Equation N-1**, to obtain sufficient data points to attain the desired power level with the statistical tests and allow for possible lost or unusable data. The value of 20 percent is selected to account for a reasonable amount of uncertainty in the parameters used to calculate *N* and still allow flexibility to account for some lost or unusable data. The recommended 20 percent correction factor should be applied as a minimum value. Experience and site-specific considerations should be used to increase the correction factor if required. If the user determines that the 20 percent increase in the number of measurements is excessive for a specific site, a retrospective power analysis should be used to demonstrate that the survey design provides adequate power to support the decision (refer to **Appendix M**). When the Quantile test is applied in Scenario B, the sample size for the WRS test is used.

N.3 The Sign Test

The steps required to determine the number of data points for the Sign test are described in this section.

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1 **Equation N-1** is the simplified case in which the number of samples in the survey unit (*n*) is equal to the number of samples in the reference area (*m*). If *n* and *m* are not equal, refer to NUREG-1505, Revision 1 (NRC 1998a).

2 The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

N.3.1 Determine P_S

For Scenario A, P_S is the estimated probability that a random measurement from the survey unit will be less than the UBGR or $DCGL_W$ when the survey unit median is actually at the LBGR and is used only when the radionuclide is not present in background. P_S is used in **Equation N-2** to calculate the minimum number of data points necessary for the survey to meet the Data Quality Objectives. The value of the relative shift calculated in **Section 5.3** is used to obtain the corresponding value of P_S from **Table N-3.**

For Scenario B, P_S is the estimated probability that a random measurement will be greater than the LBGR when the median is near the discrimination limit or UBGR.

N.3.2 Determine Decision Error Percentiles

The next step in this process is to determine the percentiles, $Z_{1-\alpha}$ and $Z_{1-\beta}$, represented by the selected decision error levels, α and β, respectively (refer to **Table N-2**).

N.3.3 Calculate Number of Data Points for the Sign Test

The number of data points, *N*, to be obtained for the Sign test is next calculated using the following formula:

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{4(P_s - 0.5)^2} \qquad \textbf{Equation N-2}$$

Finally, the number of anticipated data points should be increased by at least 20 percent, as discussed in **Section N.2.3**, to ensure sufficient power of the tests and to allow for possible data losses.

Table N-3 Values of P_s for Given Values of the Relative Shift, Δ/σ, When the Radionuclide Is Not Present in Background[1]

Δ/σ	P_S	Δ/σ	P_S
0.1	0.539828	2.1	0.982136
0.2	0.579260	2.2	0.986097
0.3	0.617911	2.3	0.989276
0.4	0.655422	2.4	0.991802
0.5	0.691462	2.5	0.993790
0.6	0.725747	2.6	0.995339
0.7	0.758036	2.7	0.996533
0.8	0.788145	2.8	0.997445
0.9	0.815940	2.9	0.998134
1.0	0.841345	3.0	0.998650
1.1	0.864334	3.1	0.999032
1.2	0.884930	3.2	0.999313

Δ/σ	P_S	Δ/σ	P_S
1.3	0.903199	3.3	0.999517
1.4	0.919243	3.4	0.999663
1.5	0.933193	3.5	0.999767
1.6	0.945201	4.0	0.999968
1.7	0.955435	5.0	1.000000
1.8	0.964070	6.0	1.000000
1.9	0.971284		
2.0	0.977250		

[1] If $\Delta/\sigma > 6.0$, use P_S = 1.000000

APPENDIX O
UPPER CONFIDENCE LIMIT SIMULATION FOR SITE-SPECIFIC SCANNING SURVEYS WHERE THE RADIONUCLIDE IS PRESENT IN BACKGROUND

Simulation can be used to verify the results of statistical tests or as another method to perform statistical calculations. Solving the same problem from **Section 8.5.2**, using multiple methods can provide confidence in the results of an analysis. The calculation of the upper bound of the *t*-interval difference of the means result was verified using Monte Carlo and bootstrap methods. Monte Carlo analysis is typically used to evaluate the uncertainty in a result considering the uncertainty in a number of input parameters. The uncertainty in a result can be estimated by repeated sampling from specified distributions of uncertain parameters. Next, the sets of sampled input parameter values are run through a model (e.g., environmental transport model), and a distribution of a key output or result computed (e.g., peak dose over time). The distribution of output results reflects the uncertainty in the inputs. Statistics on the output can be calculated (e.g., 95th percentile of the output distribution such as peak dose). Bootstrap is a resampling procedure that uses data from a single sample from a population to generate a sampling distribution by repeated sampling of the initial sample with replacement. A key parameter of interest can be calculated for each resample (e.g., mean[1] concentration), and statistics on the parameter can computed (e.g., 95th percentile of the mean).

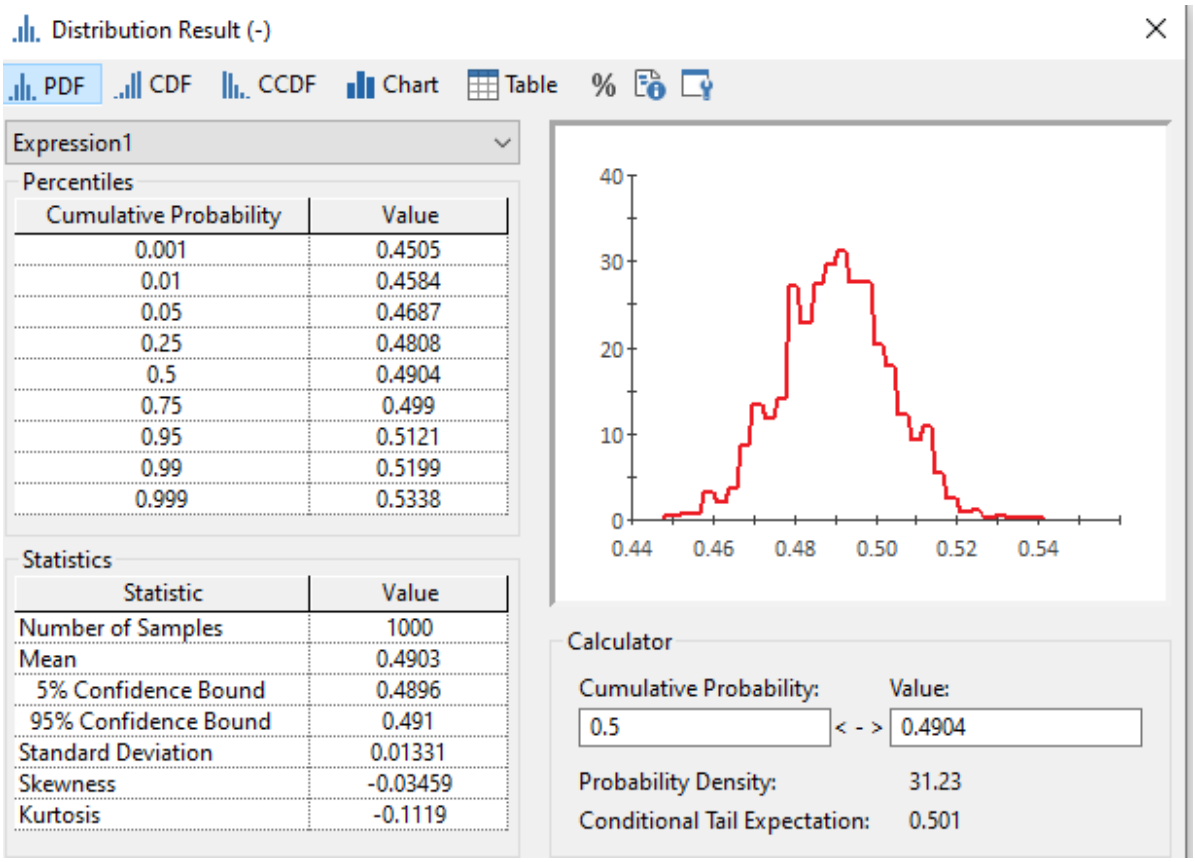
For the purposes of this example, suppose two samples representing survey unit and reference area counts per second are available from radiological surveys. These sets of measurements can be sampled with replacement, and then a parameter of interest (e.g., mean difference between the two samples) can be calculated for the set of resampled values repeatedly. Statistics on the parameter of interest can be calculated, such as the 95th percentile of the mean. This problem can be solved using Monte Carlo or bootstrap methods, as described below.

[1] In the Multi-Agency Radiation Survey and Site Investigation Manual, “average” and “mean” both refer to the arithmetic mean.

Example O-1: Use of Monte Carlo and Bootstrap Methods to Verify the *t*-Interval Example in Section 8.5.2

To verify the results for the *t*-interval example in **Section 8.5.2**, a simulation was performed using the GoldSim™ modeling platform to simulate a problem similar to the one above to check the accuracy of the results. First, the survey unit and reference area distributions were specified in GoldSim™, as indicated in the example in **Section 8.5.2** (normal distributions with means of 1.5 and 1.01 and standard deviations of 0.3 for the survey unit and reference area, respectively).

Next, 10,000 values were sampled from the distributions to create a distribution of differences between survey unit and reference area measurements. This distribution was transferred to a submodel and sampled (e.g., 1,000 samples), and the mean from each set of samples was calculated. The 95th percentile value of the mean difference was calculated. Similar results were obtained from the GoldSim™ simulation as for the example in **Section 8.5.2**. The 95th percentile of the mean was reported as 0.5121. The figure below shows the distribution of means output from GoldSim™.



It is important to note that a different sampling of values in this example will result in a slightly different answer. That is because confidence intervals change for every sample used to generate the confidence interval. Additionally, the confidence interval will change as a result of a change in the desired confidence limit or a change in the number of resamples, as discussed below. In reality, site-specific scanning surveys are expected to have a very large number of samples, making this calculation trivial (i.e., the result will approach the difference between the means of the survey unit and references area as the number of samples approaches infinity).

The distribution of differences created in GoldSim™ was copied and pasted into Microsoft Excel™ to perform a bootstrap analysis to calculate the 95th percentile of the mean. The survey unit and reference area distributions can also be sampled in Microsoft Excel™ using the formula "=(NORM.INV(RAND(),μ_r,σ_r))", where μ_r is the reference area mean and σ_r is the reference area standard deviation (the same formula would be used to sample the survey unit). The differences between the sampled survey unit and reference area would then be calculated. The differences were labeled "sample" as a set of values from which a number of samples could be taken with replacement using the formula "=INDEX(sample,RANDBETWEEN(1,ROWS(sample)),1)". The "sample" of differences was resampled 1,000 times using bootstrap methods with replacement. The mean of the resampled values was calculated. The resampling and calculation of the mean was repeated 1,000 times. The 95th percentile of the mean was extracted from the distribution of 1,000 mean values. A different number of resamples can be taken from the "sample" of differences, and this resampling process can be performed a different number of times as described below.

The following numbers of resamples (e.g., 10, 100, 500, and 1,000) were taken from the "sample" of differences. As expected, the 95th percentile of the mean became stable and approached a constant number very close to the difference between the survey unit and reference area means of 0.5. The table below shows the results of the bootstrap analysis discussed above, as well as additional bootstrap analyses that reveal that a much tighter confidence interval is estimated for a lower confidence of 0.80 and that the upper confidence limit (UCL) approaches the value of 0.5 as the number of samples increases. A smaller "sample" of 1,000 differences (versus 10,000), sampled 1,000 times to produce the 95th UCL of the mean, also resulted in a value of 0.511 as shown in **bold** text below.

# of resamples	80th UCL of the mean 1,000 differences/ 1,000 samples	95th UCL of the mean 1,000 differences/ 1,000 samples	80th UCL of the mean 10,000 differences/ 1,000 samples	95th UCL of the mean 10,000 differences/ 1,000 samples
10	0.607	0.709	0.587	0.709
100	0.528	0.558	0.515	0.549
500	0.504	0.520	0.495	0.501
1000	0.501	**0.512**	0.491	0.499

Monte Carlo and bootstrap analyses are powerful tools to perform probabilistic modeling and simulation. They can be used to verify other analytical approaches, such as for the example in **Section 8.5.2**, or to perform statistical tests in an alternative manner. With proper verification and validation, these methods can be used to simulate all sorts of problems of interest to users of this manual without the need for assumptions regarding the type of distribution or distribution parameters. The following references on bootstrap may be consulted for additional information:

- *An Introduction to the Bootstrap*, by Bradley Efron and Robert J. Tibshirani (1993): This seminal book provides an in-depth introduction to bootstrap methods, covering both theoretical foundations and practical applications (Efron and Tibshirani 1993).

- *Bootstrap Methods and Their Application*, by A.C. Davison and D.V. Hinkley (1997): This text offers a detailed exploration of bootstrap techniques, including discussions on various bootstrap schemes and their applications across different statistical models (Davison and Hinkley 1997).
- *Resampling Methods: A Practical Guide to Data Analysis*, by Phillip I. Good (2005): This book serves as a practical guide to resampling methods, including the bootstrap, with numerous examples and applications in data analysis (Good 2005).
- *The Jackknife, the Bootstrap, and Other Resampling Plans*, by Bradley Efron (1987): This monograph introduces the bootstrap and compares it with other resampling methods like the jackknife, providing insights into their relative advantages and limitations (Efron 1987).
- "Computer-Intensive Methods in Statistics," by P. Diaconis and B. Efron (1983): This article discusses the role of computer-intensive methods, including the bootstrap, in modern statistical analysis, highlighting their practical implementation and theoretical underpinnings (Diaconis and Efron 1983).

GLOSSARY

Note: Italicized terms within definitions are defined elsewhere in this glossary.

91b material: Any material identified under Section 91b of the Atomic Energy Act of 1954 (42 U.S.C. § 2121).

A_{min}: The smallest *area of elevated activity* that is important to identify using the *Data Quality Objectives process*.

action level: The numerical value that causes a decision-maker to choose or accept one of the alternative actions to the "no action" alternative. See also in this glossary *investigation level*.

activity: See in this glossary *radioactivity*.

alpha (α): The specified maximum probability of a *Type I decision error*. In other words, the maximum probability of rejecting the *null hypothesis* when it is true. *Alpha* is also referred to as the size of the test. *Alpha* reflects the amount of evidence the decision-maker would like to see before abandoning the *null hypothesis*.

alpha particle: A positively charged particle ejected spontaneously from the nucleus of an unstable atom during *radioactive decay* (or disintegration). It is identical to a helium nucleus that has a mass number of 4 and an electrostatic charge of +2. It has low penetrating power and a short range (a few centimeters in air).

alternative hypothesis (H_1): See in this glossary *hypothesis*.

area: A general term referring to any portion of a *site*, up to and including the entire *site*.

area of elevated activity: An *area* over which the *concentration* of *residual radioactive material* exceeds a specified value of the *derived concentration guideline level elevated measurement comparison ($DCGL_{EMC}$)*.

arithmetic mean: The sum of a series of measured values, divided by the number of values.

arithmetic standard deviation: A statistic used to quantify the variability of a set of data. It is calculated in the following manner: (1) subtracting the *arithmetic mean* from each data value individually, (2) squaring the differences, (3) summing the squares of the differences, (4) dividing the sum of the squared differences by the total number of data values less one, and (5) taking the square root of the quotient.

audit (quality): A systematic and independent examination to determine whether *quality* activities and related results comply with planned arrangements and whether these arrangements are implemented effectively and are suitable to achieve objectives.

background reference area: See in this glossary *reference area*.

background radiation: The natural radiation that is always present in the environment. It includes cosmic radiation, which comes from the sun and stars; terrestrial radiation, which comes from the Earth; and internal radiation, which exists in all living things. Background radiation does not include radiation from *source material*, *byproduct material*, or *special nuclear material* regulated by the cognizant Federal or State agency. Different definitions may exist for

this term. The definition provided in *regulations* or the regulatory program being used for a *site* release should always be used if it differs from the definition provided here.

becquerel (Bq): The International System (SI) unit of *activity* equal to one nuclear transformation (disintegration) per second. 1 *Bq* = 2.7×10^{-11} curies (Ci) = 27.03 picocuries (pCi).

beta (β): The probability of a *Type II decision error* (i.e., the probability of accepting the *null hypothesis* when it is false). The complement of *beta* ($1-\beta$) is referred to as the *power* of the test.

beta particle: A charged particle (with a mass equal to 1/1,837 that of a proton) that is emitted from the nucleus of an unstable atom during *radioactive decay* (or disintegration). A negatively charged *beta particle* is identical to an electron, while a positively charged *beta particle* is called a positron.

bias: The systematic or persistent distortion of a measurement process that causes error in one direction. The *bias* of a *measurement method* is 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.

biased sample or measurement: See in this glossary *judgment measurement*.

blind sample or measurement: A *sample* or *measurement* whose *concentration* is not known to the analyst. For example, *blind samples* are used to assess analytical performance. A double-*blind sample* is a *sample* whose *concentration* and identity as a *sample* are known to the submitter but not to the analyst. The double-*blind sample* should be treated as a routine *sample* by the analyst, so it is important that the double-*blind sample* is identical in appearance to routine *samples*.

building surface: The thickness of *building surface* material that can be measured using *direct measurement* or *scanning* techniques and will vary depending on *radionuclide*, surface characteristics, *measurement* technique, and pathway modeling assumptions.

byproduct material: As defined by U.S. Nuclear Regulatory Commission (NRC) regulations, it includes any radioactive material (except enriched uranium or plutonium) produced by a nuclear reactor; the tailings (wastes produced by the extraction or *concentration* of uranium or thorium, or the fabrication of fuel for nuclear reactors); any material that has been made radioactive through the use of a particle accelerator; and any discrete source of radium-226 used for a commercial, medical, or research activity. In addition, the NRC, in consultation with the U.S. Environmental Protection Agency, U.S. Department of Energy, U.S. Department of Homeland Security, and others, can designate as *byproduct material* any source of naturally occurring radioactive material, other than *source material*, that it determines would pose a threat to public health and safety or the common defense and security of the United States.

calibration: The set of operations that establish, 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 measurand.

categorization: The act or result of separating *areas* or *survey units* into one of two categories: *impacted areas* and *non-impacted areas*.

chain of custody: An unbroken trail of accountability that ensures the physical security of *samples*, data, and records.

characterization survey: A type of *survey* that includes facility or *site* sampling, monitoring, and analysis activities to determine the horizontal and vertical extent and nature of *residual radioactive material*. *Characterization surveys* provide the basis for acquiring the necessary technical information to develop, analyze, and select appropriate *cleanup* techniques.

Class 1 area: *Areas* that have, or had prior to *remediation*, a potential for *residual radioactive material* (based on *site* operating history) or known *residual radioactive material* (based on previous *radiological surveys*) above the *derived concentration guideline level for average concentrations over a wide area (DCGL$_W$)*. Examples of *Class 1 areas* include (1) *site areas* previously subjected to *remedial action*s,[1] (2) locations where leaks or spills are known to have occurred, (3) former burial or disposal *sites*, and (4) waste storage *sites*.

Class 1 survey: A type of *final status survey* that applies to *Class 1 areas*.

Class 2 area: *Areas* that have, or had prior to *remediation*, a potential for *residual radioactive material* or known *residual radioactive material*, but are not expected to exceed the *derived concentration guideline level for average concentrations over a wide area (DCGL$_W$)*. To justify changing an area's *classification* from Class 1 to Class 2, the existing data (from the *Historical Site Assessment*, *scoping surveys*, or *characterization surveys*) should provide a high degree of confidence that no individual *measurement* would exceed the *DCGL$_W$*. Other justifications for this change in an area's *classification* may be appropriate based on the outcome of the *Data Quality Objectives process*. Examples of *areas* that might be classified as Class 2 for the *final status survey* include (1) locations where radioactive materials were present in an unsealed form (e.g., process facilities), (2) transport routes with potential *residual radioactive material*, (3) *areas* downwind from stack release points, (4) upper walls, roof support frameworks, and ceilings of buildings or rooms subjected to airborne radioactive material, (5) *areas* where low *concentrations* of radioactive materials were handled, and (6) *areas* on the perimeter of former radiological control *areas*.

Class 2 survey: A type of *final status survey* that applies to *Class 2 areas*.

Class 3 area: Any *impacted areas* that are not expected to contain any *residual radioactive material* or are expected to contain *concentrations* of *residual radioactive material* at a small fraction of the *derived concentration guideline level for average concentrations over a wide area (DCGL$_W$)*, based on *site* operating history and previous *radiological surveys*. To justify changing an area's *classification* from Class 1 or Class 2 to Class 3, the existing data (from the *Historical Site Assessment*, *scoping surveys*, or *characterization surveys*) should provide a high degree of confidence that there is either no *residual radioactive material*, or that any levels of *residual radioactive material* are a small fraction of the *DCGL$_W$*. Other justifications for this change in an area's *classification* may be appropriate based on the outcome of the *Data Quality Objectives process*. Examples of *areas* that might be classified as Class 3 include buffer zones around

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[1] Remediated areas are identified as *Class 1 areas* because the *remediation process* often results in less than 100 percent removal of the *residual radioactive material.* The *residual radioactive material* that remains on the *site* after *remediation* is often associated with relatively small areas with elevated *concentrations* of radioactive material. This results in a non-uniform distribution of the *radionuclide* and a Class 1 *classification*. If an *area* is expected to have no potential to exceed the *DCGL$_W$* (i.e., a *Class 2 area* before *remediation*) and was remediated for reasons other than an exceedance of the DCGL$_W$, the remediated area would still be classified as Class 2 for the *final status survey.*

Class 1 or *Class 2 areas*, and *areas* with very low potential for *residual radioactive material* but insufficient information to justify a *non-impacted classification*.

Class 3 survey: A type of *final status survey* that applies to *Class 3 areas*.

classification: The act or result of separating *areas* or *survey units* into one of three designated classes—*Class 1 area*, *Class 2 area*, or *Class 3 area*—according to the *area*'s radiological characteristics.

cleanup: Actions taken to deal with a release or threatened release of hazardous substances that could affect public health or the environment. The term is often used broadly to describe various Superfund response actions or phases of remedial responses, such as the remedial investigation/feasibility study. *Cleanup* is sometimes used interchangeably with the terms *remedial action* and response action.

cleanup standard: A numerical limit set by a regulatory agency as a requirement for releasing a *site* after *cleanup*. See in this glossary *release criteria*.

coefficient of variation: A unitless measure that allows the comparison of dispersion across several sets of data. It is often used in environmental applications because variability (expressed as a *standard deviation*) is often proportional to the *mean*. The *coefficient of variation* of a nonnegative random variable is the ratio of its *standard deviation* to its *mean*.

committed dose equivalent (CDE): The *dose equivalent* calculated to some specific organ or tissue of reference that will be received from an intake of radioactive material by an individual during the 50-year period following the intake. It does not include contributions from radiation sources external to the body. *CDE* is expressed in units of *sieverts* or *rem*.

committed effective dose equivalent (CEDE): The sum of the *committed dose equivalents* for each of the body organs or tissues that is irradiated multiplied by the *weighting factors (W_T)* applicable to each of those organs or tissues. *CEDE* is expressed in units of *sieverts* or *rem*. See also in this glossary *total effective dose equivalent (TEDE)*.

composite sample: A *sample* formed by collecting several *samples* and combining them (or selected portions of them) into a new *sample,* which is then thoroughly mixed or homogenized.

concentration: *Activity* per unit mass or volume (e.g., *becquerels* [*Bq*] per kilogram [kg], picocuries [Ci] per gram [g], or *Bq* per cubic meter [m^3]) or *activity* per unit area (e.g., *Bq* per square meter [m^2] or disintegrations per minute [dpm] per 100 square centimeters [cm^2]).

conceptual site model: A description of a *site* and its environs and presentation of hypotheses regarding the *radionuclides* present, their routes of migration, and their potential impact on sensitive receptors.

confidence interval: An estimated range of values for which there is a specified probability (e.g., 80 percent, 90 percent, 95 percent) that this range contains the true value of an estimated parameter, such as the true *mean*, the estimated range being calculated from a given set of *sample* data.

confirmatory survey: A type of *survey* that includes limited independent (third-party) *measurements*, sampling, and analyses to confirm the findings of a *final status survey*.

consensus standard: A standard established by a group representing a cross section of a particular industry or trade, or a part thereof.

contamination: As used in the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), undesirable radioactive material deposited in, or on the surface of, an object (e.g., a radiation detection instrument) in a *concentration* that makes the object unfit for its next intended use or poses a hazard to people or the environment.

continuously collected data (CCD): *Radiological survey* and paired location data that are collected in a continuous fashion. CCD are typically collected at a constant scan speed determined as part of the *Data Quality Objectives process* in a preplanned area along a *survey* path, transect, or set of transects producing a roughly evenly spaced set of data points. For indoor areas, position data may or may not be collected. CCD in this document should not be confused with continuously recording data at a single, discrete sampling location.

control chart: A graphical representation of data taken from a repetitive *measurement* or *process*. *Control charts* may be developed for various characteristics (e.g., *mean*, *standard deviation*, range) of the data. A *control chart* has two basic uses: (1) as a tool to judge whether a *process* was in control, and (2) as an aid in achieving and maintaining *statistical control*. For applications related to radiation detection instrumentation or radiochemical *processes*, the *mean* (center line) value of a historical characteristic (e.g., *mean* detector response), subsequent data values and control limits placed symmetrically above and below the center line are displayed on a *control chart*. Run charts are a type of *control chart* where points are plotted on a graph in the order in which they become available, such as parameters plotted versus time, and used to monitor a *process* to see whether or not the long-range average is changing.

core sample: A *soil sample* taken by core drilling.

criteria: See in this glossary *release criteria*.

critical group: The group of individuals reasonably expected to receive the greatest *dose* or health risk from *residual radioactive material* for any applicable set of circumstances.

critical level (L_C): The level at which there is a statistical probability (with a predetermined confidence) of correctly identifying a background value as greater than background.

critical value: A fixed value of the *test statistic* corresponding to a given probability level, as determined from the probability distribution of the *test statistic*. The value of a statistic (t) corresponding to a given significance level as determined from its sampling distribution; for example, if $P_r(t > t_0) = 0.05$, t_0 is the *critical value* of t at the 5 percent level.

curie (Ci): The traditional unit of *radioactivity*. One *curie* (Ci) is equal to 37 billion disintegrations per second (dps) (3.7×10^{10} dps = 3.7×10^{10} *Bq*), which is approximately equal to the *decay* rate of 1 gram of radium-226. Fractions of a *curie* (e.g., picocurie [pCi], or 10^{-12} *Ci*, and microcurie [µCi], or 10^{-6} *Ci*) are levels typically encountered in *remediation*.

***D*:** The true, but unknown, value of the difference between the true *mean concentration* of *residual radioactive material* in the *survey unit* and the *reference area*.

Data Life Cycle: The *process* of planning the *survey*, implementing the *survey* plan, and assessing the *survey* results before making a decision.

Data Quality Assessment: The scientific and statistical evaluation of data to determine if the data are of the right type, *quality*, and quantity to support their intended use. See also in this glossary *data usability.*

Data Quality Objectives: Qualitative and quantitative statements derived from the *Data Quality Objectives process* that clarify study technical and *quality* objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the *quality* and quantity of data needed to support decisions.

Data Quality Objectives process: A series of logical steps that guides managers or staff to create a plan for the resource-effective acquisition of environmental data, to ensure that the survey results are of sufficient quality and quantity to support the final decision. See also in this glossary *Data Quality Objectives*.

data usability: The scientific and statistical evaluation of datasets to determine whether data are of the right type, *quality*, and quantity to support their intended use. The data *quality* assessor integrates the data *validation* report, field information, assessment reports, and historical project data to determine *data usability* for the intended decisions. See in this glossary *Data Quality Assessment.*

decay: See in this glossary *radioactive decay*.

decay product: Nuclide formed by the *radioactive decay* of a *radionuclide*.

decision rule: A statement that describes a logical basis for choosing among alternative actions. It defines how the decision-maker would choose among alternative actions if the true state of nature could be known with certainty. For decision problems, the theoretical decision rule is an unambiguous “If...then...else...” statement.

decommission: To remove a facility or *site* safely from service and reduce the *concentration* of *residual radioactive material* to a level that permits release of the property and termination of the *license* and other authorization for *site* operation.

delta: (1) As δ, the amount that the distribution of *measurements* for a *survey unit* is increased compared to the distribution of *measurements* of the *reference area*. (2) As Δ, the width of the *gray region*. *Delta* (Δ) divided by sigma (σ), the *arithmetic standard deviation* of the *measurements*, is the *relative shift* expressed in multiples of *standard deviations*. See in this glossary *relative shift, gray region*.

derived concentration guideline level for small areas of elevated activity ($DCGL_{EMC}$): Based on pathway modeling, the *concentration* of *residual radioactive material* within an area of the *survey unit* with elevated *activity* that corresponds to the *release criteria* (e.g., regulatory limit in terms of *dose* or risk).

derived concentration guideline level for average concentrations over a wide area ($DCGL_W$): Based on pathway modeling, the uniform *concentration* of *residual radioactive material* across a *survey unit* that corresponds to the *release criteria* (e.g., regulatory limit in terms of *dose* or risk). This is also known as the wide-area derived concentration guideline level.

design specification process: The *process* of determining the sampling and analysis procedures that are needed to demonstrate that the attainment objectives are achieved.

detection capability: The *net response level* that can be expected to be seen using a detector with a fixed level of confidence.

detection limit (L_D): The net response level that can be expected to be seen with a detector with a fixed level of certainty.

direct measurement: *Measurement* of radioactive material obtained by placing the detector near the surface or medium being surveyed for a prescribed amount of time. An indication of the resulting *concentration* of radioactive material is read out directly.

discrete radioactive particle: Small, usually microscopic, highly radioactive particles having relatively high specific *activity*.

discrimination limit: The level of *radioactivity* selected by the members of the *planning team* that can be reliably distinguished from the *action level*. The *upper bound of the gray region* for *Scenario B* is an example of a *discrimination limit*. See also in this glossary *gray region*, *Scenario A*, and *Scenario B*.

distribution coefficient (K_d): The ratio of elemental (i.e., *radionuclide*) *concentration* in *soil* to that in water in a *soil*-water system at equilibrium. K_d is generally measured in terms of gram weights of *soil* and volumes of water (grams per cubic centimeter [g/cm^3] or grams per milliter [g/mL]).

dose commitment: The *dose* that an organ or tissue would receive during a specified period of time (e.g., 50 or 70 years) as a result of intake (as by ingestion or inhalation) of one or more *radionuclides* from a given release.

dose equivalent (dose): A measure of the biological damage to living tissue as a result of radiation exposure. Also known as the biological *dose*, the *dose equivalent* is calculated as the product of absorbed *dose* in tissue multiplied by a *quality* factor and then sometimes multiplied by other necessary modifying factors at the location of interest. The *dose equivalent* is expressed numerically in *sieverts* or *rem*.

effective probe area: The *physical probe area* corrected for the amount of the probe area covered by a protective screen.

elevated area: See in this glossary *area of elevated activity*.

elevated measurement: A *measurement* that exceeds a specified value *derived concentration guideline level for an elevated measurement comparison ($DCGL_{EMC}$)*.

elevated measurement comparison (EMC): This comparison is used in conjunction with the *Wilcoxon Rank Sum test* and *Sign test* to determine whether there are any *measurements* that exceed a specified value *derived concentration guideline level for an elevated measurement comparison ($DCGL_{EMC}$)*.

exposure pathway: The route by which *radionuclides* travel through the environment to eventually cause radiation exposure to a person or group.

exposure pathway modeling: An analysis of various *exposure pathways* and scenarios used to convert *dose* or risk into *concentration* and used to calculate a *radionuclide*-specific predicted *concentration* of radioactive material or surface area *concentration* of radioactive material of

specific nuclides that could result in a *dose* or risk equal to the *release criteria* within the required evaluation period.

exposure rate: The amount of ionization produced per unit time in air by x-rays or *gamma (γ) radiation*. The unit of *exposure rate* is *roentgens* per hour (R/h); for *decommissioning* activities, the typical units are microroentgens per hour (µR/h) (i.e., 10^{-6} R/h).

external radiation: Exposure to ionizing radiation when the radiation source is located outside the body.

false negative decision error: The error that occurs when the *null hypothesis (H_0)* is not rejected when it is false. A statistician usually refers to a false negative error as a *Type II decision error*. The measure of the size of this error is called *beta (β)* and is also known as the complement of the *power* of a *hypothesis* test.

false positive decision error: A *false positive decision error* occurs when the *null hypothesis (H_0)* is rejected when it is true. A statistician usually refers to the false positive error as a *Type I decision error*. The measure of the size of this error is called *alpha (α)*, the level of significance, or the size of the critical region.

Field Sampling Plan: A document that describes the number, type, and location of *samples* and the type of analyses to be performed. It is part of the *Sampling and Analysis Plan*.

final status survey (FSS): *Measurements* and sampling to describe the radiological conditions of a *site*, following completion of *remediation* activities (if any) in preparation for release. The FSS is the *survey* in the Radiation *Survey* and Site Investigation *process* that is used to demonstrate compliance with the *release criteria*.

fluence: The number of photons or particles passing through a cross-sectional area. The International System (SI) unit for *fluence* is m^{-2}.

gamma (γ) radiation: Penetrating, high-energy, short-wavelength electromagnetic radiation (similar to x-rays) emitted during *radioactive decay*. *Gamma radiation* is very penetrating and requires dense materials (such as lead or steel) for shielding.

geographic information system (GIS): A collection of computer hardware, software, geographic data, and personnel designed to capture, store, process, analyze, and visualize all forms of geographically referenced information.

graded approach: The *process* where the level of application of managerial controls for an item or work is determined according to the intended use of the results and the degree of confidence needed in the *quality* of the results. See also in this glossary *Data Quality Objectives process*.

gray region: A range of values of the parameter of interest for a *survey unit* where the consequences of making a decision error are relatively minor. In *Scenario A*, the *upper bound of the gray region (UBGR)* is set equal to the *derived concentration guideline level for average concentrations over a wide area ($DCGL_W$)*, and the *lower bound of the gray region (LBGR)* is chosen on a *site*-specific basis. In *Scenario B*, the *UBGR* is set equal to the *discrimination limit*, and the *LBGR* is set equal to the *action level*.

grid: A network of parallel horizontal and vertical lines forming squares on a map that may be overlaid on a property parcel for the purpose of identification of exact locations. See also in this glossary *reference coordinate system*.

grid block: A square defined by two adjacent vertical and two adjacent horizontal reference *grid* lines.

gross alpha activity concentration: A measured quantity in units of *activity* per some area of volume measuring the total *radioactivity* of all alpha particle emitters in a *sample*.

gross beta activity concentration: A measured quantity in units of *activity* per some area of volume measuring the total *radioactivity* of all beta particle emitters in that *sample*.

half-life ($t_{1/2}$): The time in which one half of the atoms of a particular radioactive substance disintegrate into another nuclear form. Also called physical or radiological *half-life*.

Historical Site Assessment: A detailed investigation to collect existing information, primarily historical, on a *site* and its surroundings.

hot measurement: See in this glossary *elevated measurement*.

hot particle: See in this glossary *discrete radioactive particle*.

hot spot: See in this glossary *area of elevated activity*.

hypothesis: An assumption about a property or characteristic of a set of data under study. The goal of *statistical inference* is to decide which of two complementary *hypotheses* is likely to be true. The *null hypothesis* (H_0) describes what is assumed to be the true state of nature, and the *alternative hypothesis* (H_1) describes the opposite situation.

impacted area: Any *area* that is not *categorized* as *non-impacted*. As such, they are *areas* with a possibility of containing *residual radioactive material* in excess of natural background or fallout levels.

independent assessment: An assessment performed by a qualified individual, group, or *organization* that is not part of the *organization* directly performing and accountable for the work being assessed.

indistinguishable from background: The state where the detectable *concentration* distribution of a *radionuclide* is not statistically different from the background *concentration* distribution of that *radionuclide* in the vicinity of the *site* or, in the case of structures, in similar materials using adequate *measurement* technology, *surveys*, and statistical techniques.

infiltration rate: The rate at which a quantity of a hazardous substance moves from one environmental medium to another (e.g., the rate at which a quantity of a *radionuclide* moves from a source into and through a volume of *soil* or solution).

inspection: An activity such as measuring, examining, testing, or gauging one or more characteristics of an entity and comparing the results with specified requirements to establish whether conformance is achieved for each characteristic.

integrated measurement: *Measurement* of the total number of counts observed in a specific period of time.

inventory: Total residual quantity of licensed radioactive material at a *site*.

investigation level: A derived media-specific, *radionuclide*-specific *concentration* that is based on the *release criteria*, that, if exceeded, triggers a response, such as further investigation or *remediation*. See also in this glossary *action level*.

ionizing radiation: High-energy radiation, such as a stream of x-rays, capable of ionizing the substances through which it passes.

isopleth: A line drawn through points on a graph or plot at which a given quantity has the same numerical value or occurs with the same frequency.

isotopomer: An isotopic isomer, or an isomer with the same number of each isotopic atom but differing in their positions.

judgment measurement: *Measurements* performed at locations selected using *professional judgment* based on factors such as unusual appearance, location relative to known contaminated *areas*, high potential for *residual radioactive material*, and general supplemental information. *Judgment measurements* are not included in the statistical evaluation of the *survey unit* data, because they violate the assumption of randomly selected, independent *measurements*. Instead, *judgment measurements* are individually compared to the *derived concentration guideline level for average concentrations over a wide area ($DCGL_W$)*. A *judgment measurement* is also referred to as a *biased measurement*.

karst terrain: A kind of terrain with characteristics of relief and drainage arising from a high degree of rock solubility. The majority of karst conditions occur in limestone areas, but karst may also occur in areas of dolomite, gypsum, or salt deposits. Features associated with *karst terrain* may include irregular topography, abrupt ridges, sink holes, caverns, abundant springs, and disappearing streams. Well-developed or well-integrated drainage systems of streams and tributaries are generally not present.

less-than data: *Measurements* that are reported as less than some value, such as the *action level* or *minimum detectable concentration*.

license: A *license* issued under the *regulations* in parts 30 through 35, 39, 40, 60, 61, 70, or 72 of 10 CFR Chapter I.

licensee: A company, *organization*, institution, or other entity to which the U.S. Nuclear Regulatory Commission or an Agreement State has granted a general *license* or specific *license* to construct or operate a nuclear facility, or to receive, possess, use, transfer, or dispose of *source material*, *byproduct material*, or *special nuclear material*.

license termination: Discontinuation of a *license*, the eventual conclusion to *decommissioning*.

lower bound of the gray region (LBGR): The *radionuclide concentration* or level of *radioactivity* that corresponds with the lowest value in the range where the consequence of decision errors is relatively minor. For *Scenario A*, the *LBGR* is chosen to represent a conservative estimate of the *concentration* of *residual radioactive material*. For *Scenario B*, the *LBGR* corresponds to the *action level*.

lower limit of detection (L_D): The smallest amount of radioactive material that will yield a net *measurement* (e.g., counts above background) that will be detected with at least 95 percent

probability and with no greater than a 5 percent probability of falsely concluding that a background observation represents a real positive *measurement* (above background).

***m*:** (1) As used to describe *measurement processes*, the number of *measurements* from the *reference area* used to conduct a statistical test. (2) As used for a unit of *measurement*, meters (m).

mean: See in this glossary *arithmetic mean.*

measurand: A quantity, object, or physical property intended to be measured.

measurement: For the purpose of MARSSIM, it is used interchangeably to mean (1) the act of using a detector and associated recording system to determine the level or quantity of radioactive material on a surface or in a *sample* of material removed from a medium being evaluated, or (2) the quantity obtained by the act of measuring.

measurement method: Combination of a *measurement* technique and an instrument.

measurement method uncertainty: See in this glossary *method uncertainty (u_M)*.

measurement performance criteria: Acceptance limits selected for project-specific sampling and analytical systems that will be used to judge whether project *quality* objectives are met.

Measurement Quality Objectives: The specific analytical data requirements of the *Data Quality Objectives*.

measurement sensitivity: A radiation level or quantity of radioactive material that can be measured or detected with some known or estimated level of confidence. See in this glossary *detection capability*.

measurement standard deviation: See in this glossary *standard deviation (as used in MARSSIM) (σ_M)*.

measurement uncertainty: See in this glossary *uncertainty (as used in MARSSIM) ($u(x)$)*.

median: That value above which and below which half the population lies.

method range: The lowest and highest *concentration* of a *radionuclide* of concern that a method can accurately detect.

method specificity: The ability of the method to measure the *radionuclide* of concern in the presence of interferences.

method uncertainty (u_M): The predicted *uncertainty* of the measured value that would be calculated if the method were applied to a hypothetical *sample* with a specified *concentration*, typically the release limit.

micrometeorology: The study of weather conditions in a local or very small *area*, such as immediately around a tree or building, that can affect meteorological conditions.

minimum detectable concentration (MDC): The a priori *activity concentration* that a specific instrument and technique that has a specified probability (typically 95 percent) of producing a net count (or count rate) above the critical level. When stating the *detection capability* of an

instrument, this value should be used. The *MDC* is the *lower limit of detection* (L_D) multiplied by an appropriate conversion factor to give units of *activity*.

minimum detectable count rate: The a priori count rate that a specific instrument and technique can be expected to detect.

missing or unusable data: Data (*measurements*) that are mislabeled, lost, or do not meet *quality control* standards. *Less-than data* are not considered to be *missing or unusable data*. See in this glossary *R*.

munitions: All ammunition products and components produced for or used by the armed forces for national defense and security, including ammunition products or components under the control of the U.S. Department of Defense, the U.S. Coast Guard, the U.S. Department of Energy, and the National Guard.

***N*:** The total number of *measurements* required from the *reference area* (*m*) and a *survey unit* (*n*). See in this glossary *m* and *n*.

***n*:** Number of *measurements* from a *survey unit* used to conduct a statistical test.

naturally occurring or accelerator-produced radioactive material (NARM): Radioactive material that is naturally occurring or accelerating produced, such as radium, and not classified as *source material*.

naturally occurring radioactive material (NORM): Materials containing any of the *radionuclides* produced during the formation of the earth or by interactions of terrestrial matter with cosmic rays as they occur in nature. Examples include radium, uranium, thorium, potassium, and their *radioactive decay products* that are undisturbed as a result of human activities.

nonconformance: A deficiency in characteristic, documentation, or procedure that renders the *quality* of an item or activity unacceptable or indeterminate; nonfulfillment of a specified requirement.

non-impacted: A term applied where there is no reasonable potential to contain *concentrations* of *residual radioactive material* above background. See also in this glossary *background radiation* and *impacted area*.

nonparametric test: A test based on relatively few assumptions about the exact form of the underlying probability distributions of the *measurements*. As a consequence, *nonparametric tests* are generally valid for a fairly broad class of distributions. The *Wilcoxon Rank Sum test* and the *Sign test* are examples of *nonparametric tests*.

non-real property: Property that is not *real property*. *Non-real property* is outside the scope of MARSSIM. See in this glossary also *real property*.

normal (gaussian) distribution: A family of bell-shaped distributions described by the *mean* and variance.

null hypothesis (H_0): See in this glossary *hypothesis*.

operational derived concentration guideline level: Any modification or combination of *radionuclide*-specific DCGLs to derive a measurable quantity (e.g., a gross beta *activity* DCGL).

outlier: *Measurements* that are unusually large or small relative to the rest and therefore are suspected of not being representative of the population from which they were collected.

p**:** The probability that a random *measurement* from the *survey unit* is less than *delta (*Δ*)*.

P_r**:** The probability that a *measurement* performed at a random location in the *survey unit* is greater than a *measurement* performed at a random location in the *reference area*.

physical probe area: The physical surface area assessed by a detector. The *physical probe area* is used to make probe area corrections in the *activity* calculations.

planning team: The *planning team* consists of representatives of all the parties who have a vested interest or can influence the outcome (stakeholders), such as program and project managers; regulators; the public; project engineers; health and safety advisors; and specialists in statistics, health physics, chemical analysis, radiochemical analysis, field sampling, *quality assurance*, *quality control*, data assessment, hydrology and geology, contract management, and field operation. The project *planning team* will define the decision(s) to be made (or the question the project will attempt to resolve) and the inputs and boundaries to the decision using a directed planning *process*.

power (1−β**):** The probability of rejecting the *null hypothesis* when it is false. The *power* is equal to one minus the *Type II decision error* rate (i.e., (1−β)).

power curve: A graph of the *power* as a function of the true value of the parameter of interest. See also in this glossary *power.*

precision: One of the historical data *quality indicators* recommended for quantifying the amount of error in *survey* data. *Precision* represents that portion of the *measurement method uncertainty* due to random *uncertainty*. It is a measure of agreement among replicate measurements of the same sampled object or property under prescribed similar conditions.

process: A combination of people, machines and equipment, methods, and the environment in which they operate to produce a given product or service.

professional judgment: An expression of opinion based on technical knowledge and professional experience, assumptions, algorithms, and definitions, as stated by an expert in response to technical problems.

quality: The totality of features and characteristics of a product or service that bear on its ability to meet the stated or implied needs and expectations of the user.

quality assurance: 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 by the customer.

Quality Assurance Project Plan: A written document outlining the procedures a monitoring project will use to ensure the data it collects and analyzes meet project requirements.

quality control: The overall system of technical activities that measure the attributes and performance of a *process*, item, or service against defined standards to verify that they meet the stated requirements established by the customer, operational techniques, and activities that are used to fulfill requirements for *quality*.

quality indicators: Measurable attributes of the attainment of the necessary *quality* for a particular environmental decision. Indicators of *quality* include *precision*, *bias*, completeness, representativeness, *reproducibility*, comparability, and statistical confidence.

Quality Management Plan: A formal document that describes the *quality system* in terms of the organizational structure, functional responsibilities of management and staff, lines of authority, and required interfaces for those planning, implementing, and assessing all activities conducted.

quality system: A structured and documented management system describing the policies, objectives, principles, organizational authority, responsibilities, accountability, and implementation plan of an *organization* for ensuring *quality* in its work *processes*, products (items), and services. The *quality system* provides the framework for planning, implementing, and assessing work performed by the *organization* and for carrying out required *quality assurance* and *quality control*.

Quantile test: A statistical test used in *Scenario B* to identify *areas* of non-uniform contamination.

***R*:** As a variable, the rate of missing or unusable *measurements* expected to occur for *samples* collected in *reference areas* or *survey units*. See in this glossary *missing or unusable data*. Not to be confused with the symbol for the radiation exposure unit *roentgen (*R*)*.

***R_A*:** The acceptable level of risk associated with not detecting an *area of elevated activity* of area A_{min}.

radioactive decay: The spontaneous transformation of one *radionuclide* into one or more different nuclides (known as *decay products* or daughter products). This transformation takes place over a defined period of time (known as a *half-life [$t_{1/2}$]*), as a result of electron capture; fission; or the emission of alpha particles, beta particles, or photons (*gamma [γ] radiation* or x-rays) from the nucleus of an unstable atom. Each nuclide in the sequence (known as a decay chain) decays to the next until it forms a stable, less energetic end product. In addition, *radioactive decay* may refer to gamma-ray and conversion electron emission, which only reduces the excitation energy of the nucleus.

radioactive equilibrium: One of three distinct relationships that arise when a *radionuclide decays* and creates *decay products* that are also radioactive: (1) Secular equilibrium occurs when the *half-life* of the *decay products* is much less than the *half-life* of the parent. For a single *decay product*, the total *activity* reaches a maximum of about twice the initial *activity* and then displays the characteristic *half-life* of the parent, usually no change over normal *measurement* intervals. (2) Transient equilibrium occurs when the *half-life* of the *decay product* is less than the *half-life* of the parent. For a single *decay product*, total *activity* passes through a maximum and then decreases with the characteristic *half-life* of the parent. (3) No equilibrium occurs when the *half-life* of the *decay product* is greater than the *half-life* of the parent. Total *activity* decreases continually after time zero.

radioactivity: The property possessed by some elements (such as uranium) of spontaneously emitting energy in the form of radiation as a result of the *decay* (or disintegration) of an unstable atom. Also the *mean* number of nuclear transformations occurring in a given quantity of radioactive material per unit time. The International System (SI) unit of *radioactivity* is the *becquerel (Bq)*. The traditional unit is the *curie (Ci)*.

radiological survey: *Measurements* of radiation levels and *concentrations* of radioactive material associated with a *site* together with appropriate documentation and data evaluation.

radioluminescence: Light produced by the absorption of energy from ionizing radiation.

radionuclide: An unstable nuclide that undergoes *radioactive decay*.

readily removable: A qualitative statement of the extent to which a *radionuclide* can be removed from a surface or medium using non-destructive, common housekeeping techniques (e.g., washing with moderate amounts of detergent and water) that do not generate large volumes of radioactive waste requiring subsequent disposal or produce chemical wastes that are expected to adversely affect public health or the environment.

real property: Developed or undeveloped land, fixed buildings and structures, or surface and subsurface *soil* remaining in place. See also in this glossary *non-real property*.

reclassification: The act or result of changing the *classification* of an *area* or *survey unit*.

reference area: Geographical *area* from which representative reference *measurements* are performed for comparison with *measurements* performed in specific *survey units*. A *site* radiological *reference area* is defined as an *area* that has similar physical, geological, chemical, radiological, and biological characteristics as the *survey unit (s)* being investigated but that has not been affected by *site* activities (i.e., *non-impacted*).

reference coordinate system: A *grid* of intersecting lines referenced to a fixed *site* location or benchmark. Typically, the lines are arranged in a perpendicular pattern dividing the *survey* location into squares or blocks of equal *areas*. Other patterns include three-dimensional and polar coordinate systems.

regulation: A rule, law, order, or direction from Federal or State governments regulating action or conduct. *Regulations* concerning radioisotopes in the environment in the United States are shared by the U.S. Environmental Protection Agency, the U.S. Nuclear Regulatory Commission, the U.S. Department of Energy, and many State governments. Federal regulations and certain directives issued by the U.S. Department of Defense (DoD) are enforced within the DoD.

relative shift (Δ/σ): *Delta* (Δ) divided by sigma (σ), the *standard deviation* of the *measurements*. See in this glossary *delta*.

relative standard deviation: See in this glossary *coefficient of variation*.

release criteria: Regulatory limits that a *survey unit* must meet before it can be released, expressed either in terms of the *dose* or risk to a future occupant of the *site* or as a *concentration* of radioactive material specified by the applicable *regulation* or standard.

rem (roentgen equivalent man): The traditional unit of *dose equivalent*. The corresponding International System (SI) unit is the *sievert (Sv)*: 1 Sv = 100 *rem*.

remedial action: An action consistent with a permanent *remedy* either instead of or in addition to a *removal* action in the event of a release or threatened release of a hazardous substance into the environment. A *remedial action* is intended to prevent or minimize the release of hazardous substances so that they do not migrate and cause substantial danger to present or future public health or welfare or the environment.

remediation: *Cleanup* or other methods used to remove or contain hazardous materials. *Remediation* includes those actions that are consistent with a permanent *remedy* taken instead of, or in addition to, a *removal* action in the event of a release or threatened release of a hazardous substance into the environment. *Remediation* is intended to prevent or minimize the release of hazardous substances so that they do not migrate to cause substantial danger to present or future public health or welfare or the environment.

remediation control survey: A type of *survey* that includes monitoring the progress of *remedial action* by the real-time *measurement* of *areas* being remediated to determine whether efforts are effective and to guide further *remediation* activities.

remedy: The method that the U.S. Environmental Protection Agency has determined will best address, correct, or remediate the contamination concerns at the *site*.

removable activity: Surface *activity* that is *readily removable* by wiping the surface with moderate pressure and can be assessed with standard radiation detectors. It is usually expressed in units of disintegrations per minute (dpm)/100 square centimeters (cm^2).

removal: As defined in EPA 402-R-08-005, "Technical Report on Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining," issued April 2008 (EPA 2008), the *cleanup* or *removal* of released hazardous substances, pollutants, or contaminants that may present an imminent and substantial danger; such actions as may be necessary in the event of the threat of release of hazardous substances into the environment; such actions as may be necessary to monitor, assess, and evaluate the threat of release of hazardous substances; the removal and disposal of material; or the taking of other such actions as may be necessary to prevent, minimize, or mitigate damage to the public health or welfare or the environment.

replicate: A repeated analysis of the same *sample* or repeated *measurement* at the same location.

representative measurement: A *measurement* that is selected using a procedure in such a way that it, in combination with other *representative measurements*, will give an accurate representation of the phenomenon being studied.

reproducibility: The *precision*, usually expressed as a *standard deviation*, that measures the variability among the results of *measurement* of the same *sample*.

residual radioactive material: Radioactive material in structures, materials, *soils*, groundwater, and other media at a *site* resulting from activities under the cognizant *organization's* control. This includes radioactive material from all sources used by the cognizant *organization* but excludes radioactive material in the background as specified by the applicable *regulation* or standard. It also includes radioactive materials remaining at the *site* as a result of routine or accidental releases of radioactive material at the *site* and previous burials at the *site*, even if those burials were made in accordance with the provisions of 10 CFR Part 20, "Standards for Protection Against Radiation."

restoration: Actions to return an *area* to a usable state following *remediation*.

robust: A statistical test or method that is approximately valid under a wide range of conditions.

roentgen (R): A unit of radiation exposure equal to the quantity of ionizing radiation that will produce one electrostatic unit of electricity in 1 cubic centimeter of dry air at 0 degrees Celsius and standard atmospheric pressure.

root mean square deviation: See in this glossary *arithmetic standard deviation*.

ruggedness: The relative stability of a *measurement* technique's performance when small variations in method parameter values are made.

***s*:** The *arithmetic standard deviation* of the *mean*.

***S+*:** The *test statistic* used for the *Sign test*.

sample: (1) As used in MARSSIM, a part or selection from a medium located in a *survey unit* or *reference area* that represents the *quality* or quantity of a given parameter or nature of the whole *area* or unit; a portion serving as a specimen. (2) As used in statistics, a set of individual *measurements* drawn from a population whose properties are studied to gain information about the entire population.

sample mean: See in this glossary *arithmetic mean.*

sample standard deviation: See in this glossary *arithmetic standard deviation.*

sampling*:* The *process* of collecting a portion of an environmental medium as being representative of the locally remaining medium. The collected portion, or aliquot, of the medium is then analyzed to identify the *radionuclide* and determine the *concentration*.

Sampling and Analysis Plan: A plan that provides a *process* for obtaining data of sufficient *quality* and quantity to satisfy data needs. *Sampling and Analysis Plans* consist of two parts: (1) the *Field Sampling Plan*, which describes the number, type, and location of *samples* and the type of analyses, and (2) the *Quality Assurance Project Plan*, which describes policy, *organization*, functional activities, *Data Quality Objectives*, and measures necessary to achieve adequate data for use in selecting the appropriate *remedy*.

scanning: A *measurement* technique performed by moving a portable radiation detector at a specified speed and distance next to a surface to detect radiation.

Scenario A: Scenario that uses a *null hypothesis* that assumes the *concentration* of radioactive material in the *survey unit* exceeds the *derived concentration guideline level for average concentrations over a wide area (DCGL*$_W$). *Scenario A* is sometimes referred to as "presumed not to comply" or "presumed not clean."

Scenario B: Scenario that uses a *null hypothesis* that assumes the *concentration* of radioactive material in the *survey unit* is less than or equal to the *action level*. *Scenario B* is sometimes referred to as "*indistinguishable from background*" or "presumed clean."

scoping survey: A type of *survey* that is conducted to identify (1) *radionuclides* present, (2) relative *radionuclide* ratios, and (3) general *concentrations* and extent of *residual radioactive material*.

shape parameter (*S*): For an elliptical *area of elevated activity*, the ratio of the semi-minor axis length to the semi-major axis length. For a circle, the shape parameter is 1. A small shape parameter corresponds to a flat ellipse.

shift: See in this glossary *delta (Δ)*.

sievert (Sv): The special name for the International System (SI) unit of *dose equivalent*. 1 Sv = 100 *rem* = 1 joule per kilogram (J/kg).

Sign test: A nonparametric statistical test used to demonstrate compliance with the *release criteria* when the *radionuclide* of interest is not present in background. See also in this glossary *Wilcoxon Rank Sum test*.

simple random sampling: A sampling technique where the *samples* are selected from a larger population in which each *sample* is chosen entirely by chance and each member of the population (i.e., *sample* or *measurement* location) has an equal chance of being selected.

site: Any installation, facility, or discrete, physically separate parcel of land, or any building or structure or portion thereof, that is being considered for *survey* and investigation.

site reconnaissance: A visit to the *site* to gather sufficient information to support a *site* decision regarding the need for further action or to verify existing *site* data. *Site reconnaissance* is not a study of the full extent of *residual radioactive material* at a facility or *site* or a risk assessment.

site-specific scanning survey: Represents an approach for evaluating residual levels of radioactive material where scan *measurements* may be used to limit the number of required *direct measurements* or *samples.* In some cases, it may even be used to replace the need for *direct measurements* or *samples* for a single or multiple *survey units* as used for statistical testing.

size (of a test): See in this glossary *alpha*.

soil: The top layer of the Earth's surface, consisting of rock and mineral particles mixed with organic matter. A particular kind of earth or ground (e.g., sandy *soil*).

source material: Uranium or thorium other than that classified as *special nuclear material*.

source term: All *residual radioactive material* remaining at the *site*—including material released during normal operations, inadvertent releases, or accidents—and that which may have been buried at the *site* in accordance with 10 CFR Part 20, "Standards for Protection Against Radiation."

special nuclear material: Plutonium, uranium-233, or uranium enriched in the isotopes uranium-233 or uranium-235.

split: A *sample* that has been homogenized and divided into two or more aliquots for subsequent analysis.

standard deviation (as used in MARSSIM) (σ): A theoretical parameter describing the variability in the distribution of the *measurement*. See also in this glossary *uncertainty (as used in MARSSIM)*.

standard normal distribution: A *normal (gaussian) distribution* with a *mean* of 0 and variance of 1.

standard operating procedure: A written document that details the method for an operation, analysis, or action with thoroughly prescribed techniques and steps and that is officially approved as the method for performing certain routine or repetitive tasks.

statistical control: The condition describing a *process* from which all special causes have been removed, evidenced on a *control chart* by the absence of points beyond the control limits and by the absence of non-random patterns or trends within the control limits. A special cause is a source of variation that is intermittent, unpredictable, or unstable.

statistical inference: The *process* of using data analysis to deduce properties of an underlying probability distribution.

statistical power: The probability that a statistical test will correctly reject the *null hypothesis* (i.e., under *Scenario A*, accepting that a *site* that meets the *release criteria* truly does, and under *Scenario B*, accepting that a *site* that does not meet the *release criteria* truly does not).

stratification: The act or result of separating an *area* into two or more sub-*areas* so that each sub-*area* has relatively homogeneous characteristics, such as *concentration* of *residual radioactive material*, topology, *surface soil* type, and vegetation cover.

Student's *t*-test: Statistical hypothesis test in which the *test statistic* follows a Student's *t*-distribution under the *null hypothesis*. It is most commonly applied when the *test statistic* would follow a normal distribution if the value of a scaling term in the *test statistic* were known (typically, the scaling term is unknown and therefore a nuisance parameter).

subsurface soil sample: A *soil sample* that reflects the modeling assumptions used to develop the *derived concentration guideline level* for subsurface *soil activity*. An example would be *soil* taken deeper than 15 centimeters (6 inches) below the *soil* surface to support *surveys* performed to demonstrate compliance with 40 CFR Part 192, "Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings."

surface residual radioactive material: *Residual radioactive material* found on building or equipment surfaces and expressed in units of *activity* per surface area (becquerels per square meter [*Bq*/m^2] or disintegrations per 100 square centimeters [dpm/100 cm^2]).

surface soil: The top layer of *soil* on a *site* that is available for direct exposure, growing plants, and resuspension of particles for inhalation. *Surface soil* may also be defined as the thickness of *soil* that can be measured using *direct measurement* or *scanning* techniques. Historically, this layer has often been represented as the top 15 centimeters (6 inches) of *soil* (40 CFR Part 192), but it will vary depending on *radionuclide*, surface characteristics, *measurement method*, and pathway modeling assumptions. For the purposes of MARSSIM, *surface soil* may also include other media types, such as gravel fill, concrete, or asphalt paving, but this should specifically be discussed with the regulator.

surface soil sample: A *soil sample* that reflects the modeling assumptions used to develop the *derived concentration guideline level* for *surface soil activity*. An example would be *soil* taken from the first 15 centimeters (6 inches) of *surface soil* to support *surveys* performed to demonstrate compliance with 40 CFR Part 192, "Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings."

surrogate radionuclide: For *sites* with multiple *radionuclides*, it may be possible to measure just one of the *radionuclides* and still demonstrate compliance for all *radionuclides* present by

using surrogate *measurements*. If there is an established ratio among the *concentrations* of the *radionuclides* in a *survey unit*, then the *concentration* of every *radionuclide* can be expressed in terms of any one of them. The measured *radionuclide* is often called a *surrogate radionuclide* for the others.

survey: A systematic evaluation and documentation of radiological *measurements* with a correctly calibrated instrument or instruments that meet the sensitivity required by the objective of the evaluation.

survey plan: A plan for determining the radiological characteristics of a *site*.

survey unit: A physical *area* consisting of structures or land *areas* of specified size and shape at a *site* for which a separate decision will be made as to whether or not the unit meets the *release criteria*. *Survey units* are generally formed by grouping contiguous *site areas* with a similar use history and the same *classification* of potential for *residual radioactive material*. *Survey units* are established to facilitate the *survey process* and the statistical analysis of *survey* data.

tandem testing: Two or more statistical tests conducted using the same dataset.

technologically enhanced naturally occurring radioactive material (TENORM): Naturally occurring radioactive materials that have been concentrated or exposed to the accessible environment as a result of human activities, such as manufacturing, mineral extraction, or water processing. See in this glossary *naturally occurring radioactive material (NORM)*.

test statistic: A function of the *measurements* (or their ranks) that has a known distribution if the *null hypothesis* is true. This is compared to the *critical level* to determine if the *null hypothesis* should be accepted or rejected. See in this glossary $S+$ and W_r.

tied measurements: Two or more *measurements* that have the same value.

total effective dose equivalent (TEDE): 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 *sieverts* or *rem*. See in this glossary *committed effective dose equivalent (CEDE).*

traceability: The ability to trace the history, application, or location of an entity by means of recorded identifications. In a *calibration* sense, *traceability* relates measuring equipment to national or international standards, primary standards, basic physical constants or properties, or reference materials. In a data collection sense, it relates calculations and data generated throughput the project back to the requirements for *quality* for the project.

triangular sampling grid: A *grid* of sampling locations that is arranged in a triangular pattern. See also in this glossary *grid*.

true mean: The *mean* of all the values in the population (i.e., collection of persons, objects or items of interest.)

Type A: A method of evaluation of *uncertainty* by the statistical analysis of a series of observations. An *uncertainty* component obtained by a *Type A* evaluation is represented by a statistically estimated *standard deviation*, where the standard *uncertainty* is equal to the *standard deviation*.

Type B: A method of evaluation of *uncertainty* by means other than the statistical analysis of series of observations. An *uncertainty* component obtained by a *Type B* evaluation is represented by a quantity that may be considered an approximation to the corresponding *standard deviation*.

Type I decision error: A decision error that occurs when the *null hypothesis* is rejected when it is true. The probability of making a *Type I decision error* is represented by *alpha* (α).

Type II decision error: A decision error that occurs when the *null hypothesis* is accepted when it is false. The probability of making a *Type II decision error* is represented by *beta* (β).

true mean: The *mean* of all the values in the population (i.e., collection of persons, objects, or items of interest). Also known as a population *mean*.

uncertainty (as used in MARSSIM) ($u(x)$): A parameter associated with the result of a *measurement*, *x*, that characterizes the dispersion of the values that could reasonably be attributed to the *measurement* of *x*. It is the estimated value of $\sigma(x)$ obtained from the propagation of *uncertainty*. See also in this glossary *standard deviation*.

Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP): A consensus *quality systems* document (EPA 2005b) prepared by the Intergovernmental Data Quality Task Force, a working group made up of representatives from the U.S. Environmental Protection Agency, the U.S. Department of Defense, and the U.S. Department of Energy. Originally issued in 2005, the UFP-QAPP was developed to provide procedures and guidance for consistently implementing the national consensus standard ANSI/ASQ E4, "Quality Systems for Environmental Data and Technology Programs—Requirements with Guidance for Use," version issued in 2004, for the collection and use of environmental data at Federal facilities. (ANSI/ASQ E4 was revised as "Quality Management Systems for Environmental Information and Technology Programs—Requirements with Guidance for Use" in 2014 [ANSI/ASQ 2014].)

unity rule (mixture rule): A rule applied when more than one *radionuclide* is present at a *concentration* that is distinguishable from background and where a single *concentration* comparison does not apply. In this case, the mixture of *radionuclides* is compared against default *concentrations* by applying the *unity rule*. This is accomplished by determining (1) the ratio between the *concentration* of each *radionuclide* in the mixture and (2) the *concentration* for that *radionuclide* in an appropriate listing of default values. The sum of the ratios for all *radionuclides* in the mixture should not exceed 1.

unrestricted release: Release of a *site* from regulatory control without requirements for future radiological restrictions. Also known as unrestricted use.

upper bound of the gray region (UBGR): The *radionuclide concentration* or level of *radioactivity* that corresponds with the highest value in the range where the consequence of decision errors is relatively minor. For *Scenario A*, the *UBGR* is set equal to the *derived concentration guideline level for average concentrations over a wide area ($DCGL_W$)*. For *Scenario B*, the *UBGR* is set equal to the *discrimination limit*.

upper simultaneous limit (USL): Value that for a given background dataset is meant to provide simultaneous coverage for all *sample* observations in the dataset with a probability of $1-\alpha$ (e.g., for an $\alpha = 0.05$, the USL is the value such that all *samples* fall below the value with 95 percent confidence). In simpler terms, the USL is an estimate of the upper boundary of the largest value in the dataset.

upper tolerance limit (UTL): Limit designed to contain, but not exceed, a large fraction of the possible background *concentrations*, thus providing a reasonable upper limit on what is likely to be observed in background. For example, a UTL95-95 is the value such that 95 percent of the recorded *samples* will fall below the value 95 percent of the time.

validation: Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled. In design and development, *validation* concerns the *process* of examining a product or result to determine conformance to user needs.

verification: Confirmation by examination and provision of objective evidence that the specified requirements have been fulfilled. In design and development, *verification* concerns the *process* of examining a result of a given activity to determine conformance to the stated requirements for that activity.

verification survey: See in this glossary *confirmatory survey*.

W_r: The sum of the ranks of the adjusted *measurements* from the *reference area*, used as the *test statistic* for the *Wilcoxon Rank Sum test*.

W_s: The sum of the ranks of the *measurements* from the *survey unit*, used with the *Wilcoxon Rank Sum test*.

weighting factor (W_T): Multiplier of the equivalent *dose* to an organ or tissue used for radiation protection purposes to account for different sensitivities of different organs and tissues to the induction of stochastic effects of radiation.

Wilcoxon Rank Sum test: A nonparametric statistical test used to determine compliance with the *release criteria* when the *radionuclide* of concern is present in background. See also in this glossary *Sign test*.

working level: A special unit of radon exposure defined as any combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 megaelectron volts of potential alpha energy. This value is approximately equal to the alpha energy released from the *decay* of progeny in equilibrium with 100 picocuries of radon-222.

$z_{1-\varphi}$: The value from the *standard normal distribution* for which the fraction of the *area* less than z is $1-\varphi$, or $100 \times (1-\varphi)$ expressed as a percentage, and the fraction of the area greater than z is φ , or $100 \times \varphi$ expressed as a percentage.

INDEX