A EXAMPLE OF MARSSIM APPLIED TO A FINAL STATUS SURVEY

A.1 Introduction

This appendix presents a relatively simple example of an FSS. Portions of this example appear earlier in **Chapter 5** and **Chapter 8**. This appendix highlights the major steps for 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 larger 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** of the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) serves as a general outline for this appendix although not every point is discussed in detail. Chapters providing discussions on 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 poured into a metal form and allowed to solidify. After drying, the form and plastic were 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 and facilities. The site was then surveyed to demonstrate that the radiological conditions satisfy regulatory agency criteria for release.

[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.

A.2.1 Identify the Radionuclides of Concern

(**Section 4.3**)

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.

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 criterion is not present at the site using derived concentration guideline levels (DCGLs). The $DCGL_W$ for ^{60}Co used for evaluating survey results is 8,300 becquerels (Bq) per square meter (m^2) (5,000 disintegrations per unit time [dpm]/100 square centimeters [cm^2]) for surface residual radioactive material of structures. The $DCGL_W$ for residual radioactive material in soil is 140 Bq per kilogram (kg) (3.8 picocuries per gram [pCi/g]).[2]

A.2.3 Classify Areas Based on Residual Radioactive Material Potential

(**Section 4.6**)

This facility consists of one administration/manufacturing building situated on approximately 0.4 hectares (1.0 acres) 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 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 grass-covered. 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 meant to be generally applied.

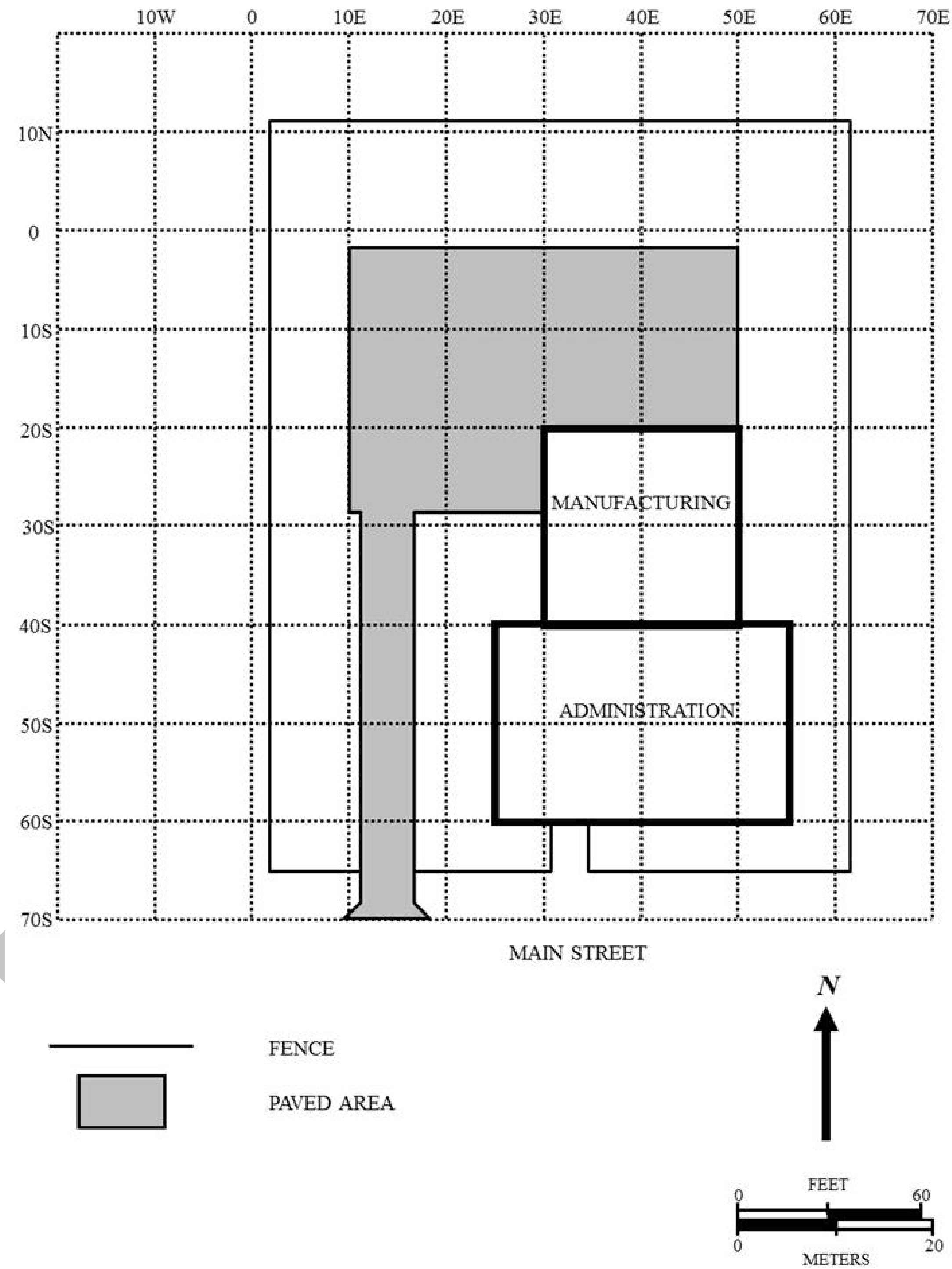


Figure A.1. Plot Plan of the Specialty Source Manufacturing Company

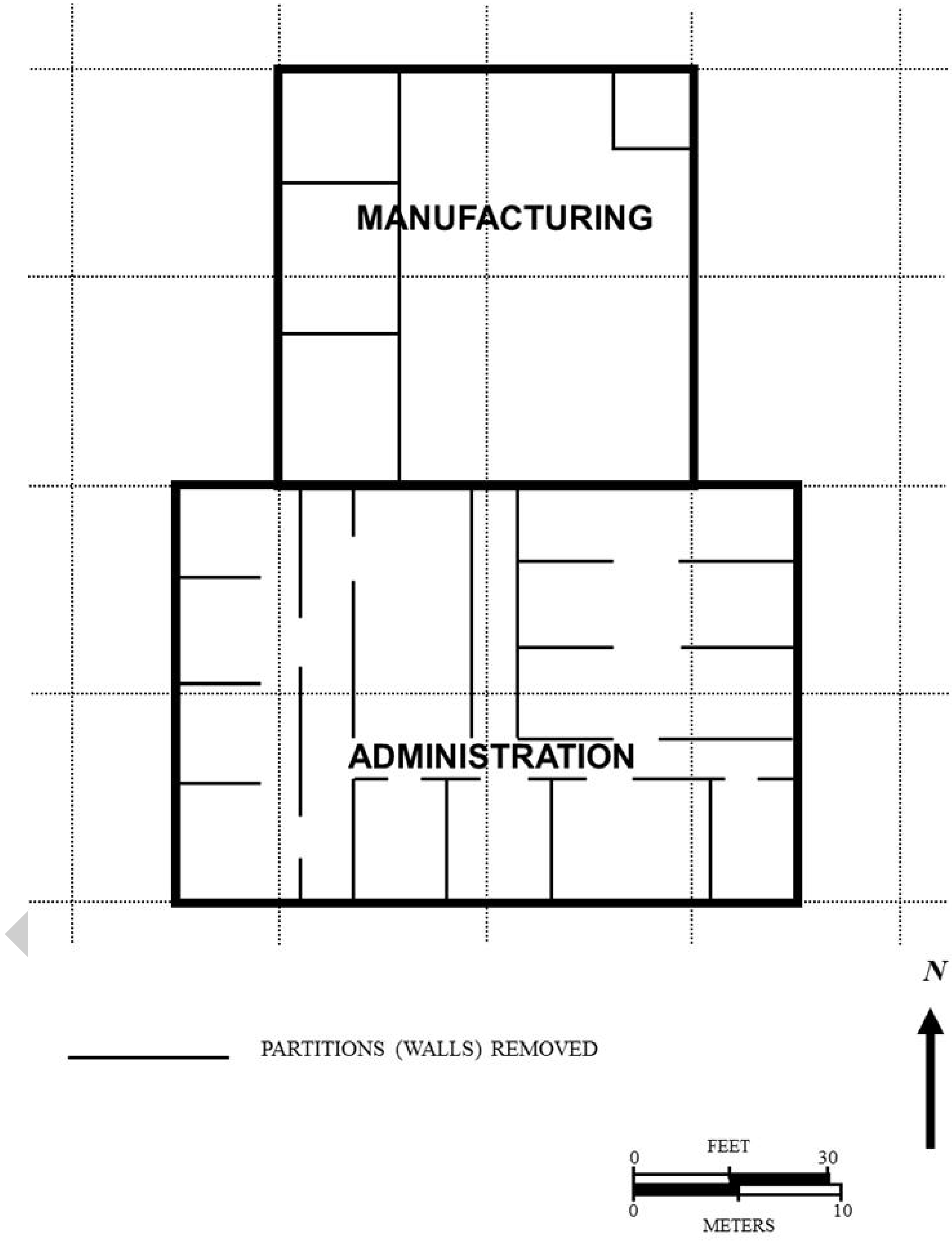


Figure A.2. Building Floor Plan

A.2.4 Identify Survey Units

(**Section 4.6**)

Based on the results of other surveys at the site and the operating history, the following survey units were used to design the FSS. All of the 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 the poured concrete and cinder block surfaces.

Structures

Class 1	Floor and lower walls (up to 2 m above the floor) of manufacturing area—4 survey units of 140 m^2 each.
Class 2	Upper walls (over 2 m above the floor) of manufacturing area—4 survey units of 100 m^2 each. Ceiling of manufacturing area—4 survey units of 100 m^2 each. Paved area outside manufacturing area roll-up door—1 survey unit of 60 m^2.
Class 3	Floors and lower walls of administration areas—1 survey unit. Remainder of paved surfaces—1 survey unit.

Land Areas

Class 3	Lawn areas—1 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. It was decided to use 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 $DCGL_{EMC}$ 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, using the gas flow proportional counter for 1-minute direct measurements yields a measurement method uncertainty of less than 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 measurement method uncertainty for using the floor monitor and the gas flow proportional counter with a scan speed of 0.5 m/s were both less than 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 soil surfaces were sampled and counted in a laboratory using a germanium (Ge) 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 sampling and laboratory analytical process combined generate a measurement method uncertainty of less than 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 NaI(Tl) scintillator with an MDC of 185 Bq/kg (5.0 pCi/g) of ^{60}Co. The measurement method uncertainty for using the NaI(Tl) scintillator with a scan speed of 0.5 m/s was less than 33 percent at the $DCGL_W$, or less than 47 Bq/kg at the $DCGL_W$ of 140 Bq/kg.

Examples of scanning patterns used in each of the Class 1, 2, and 3 areas are shown in **Figure A.3**.

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**)

Prior to 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.

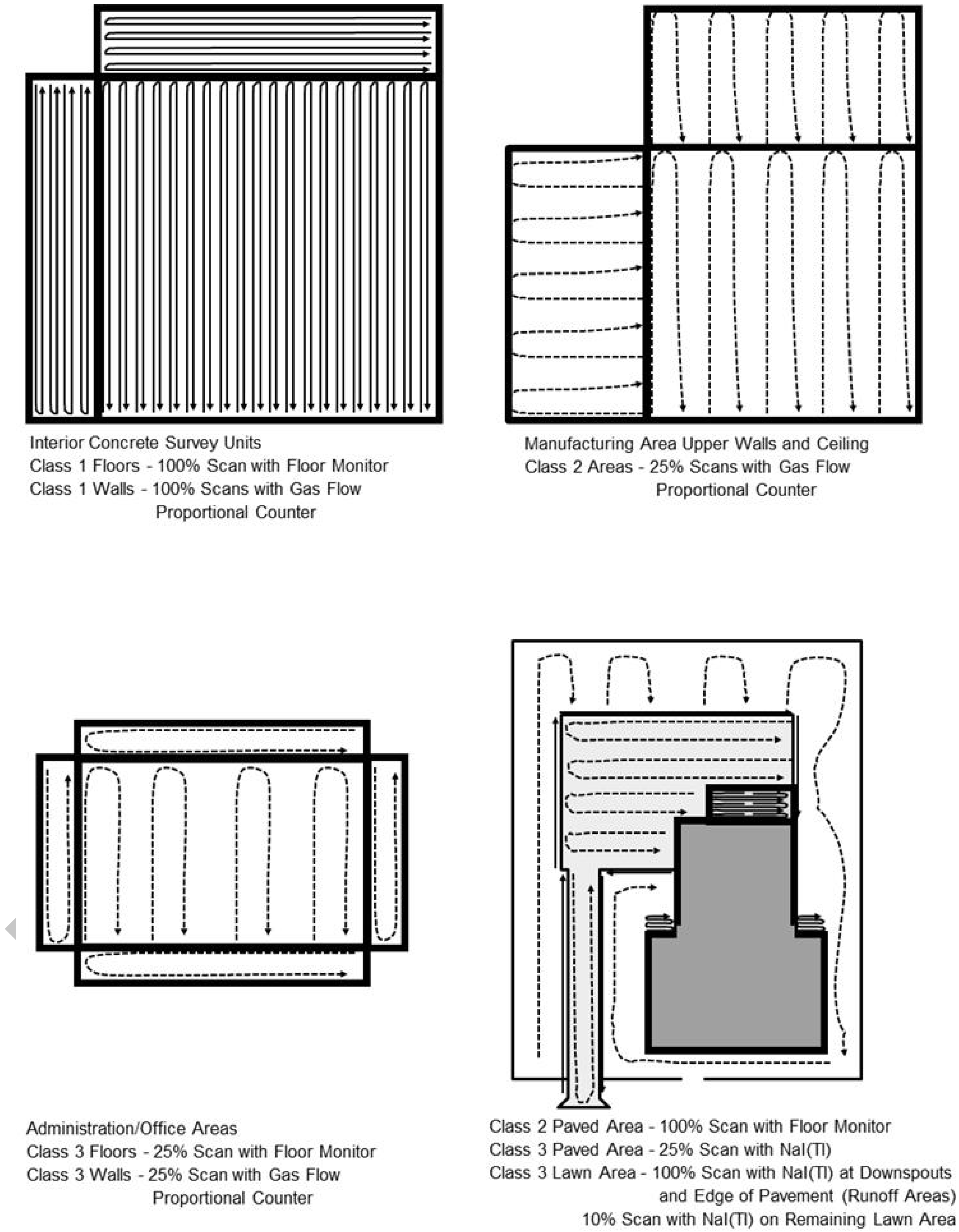


Figure A.1. Examples of Scanning Patterns for Each Survey Unit Classification

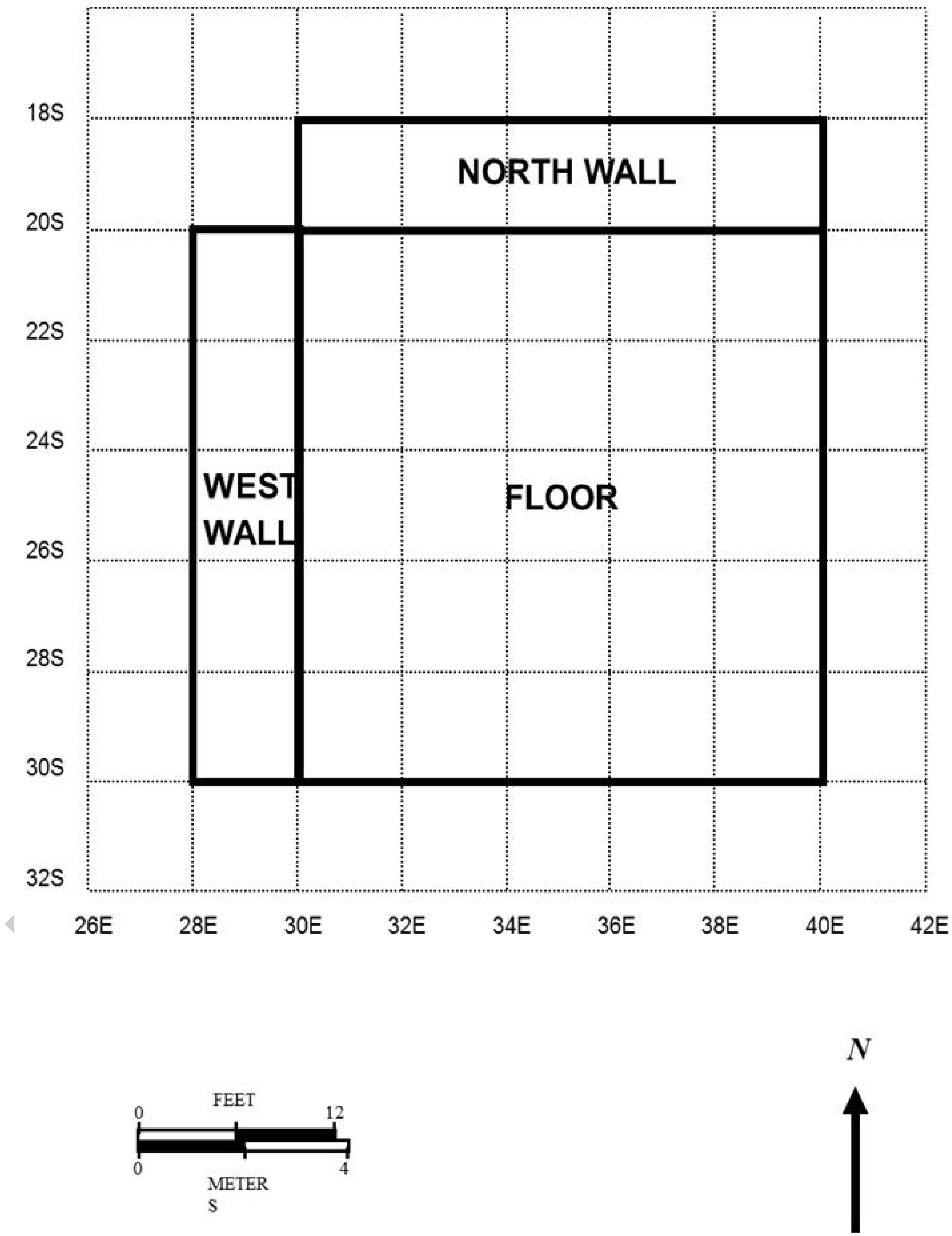


Figure A.2. Reference Coordinate System for the Class 1 Interior Concrete Survey Unit

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.

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 criterion (Scenario A). Acceptable decision error probabilities for testing the hypothesis were determined to be $\alpha = 0.05$ and $\beta = 0.05$ for the Class 1 interior concrete survey units, and $\alpha = 0.025$ and $\beta = 0.05$ for all other survey units.

A.3.2 Construct the Desired Power Curve

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

The desired power curve for the Class 1 interior concrete survey units is shown in **Figure A.5**. 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 criterion. 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.

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 prior to shipment to the analytical laboratory. At the laboratory, the samples were weighed, dried, and weighed again. The samples were ground to a uniform particle size to homogenize the samples. A germanium detector with multichannel analyzer was used to gamma count 100 g aliquots.

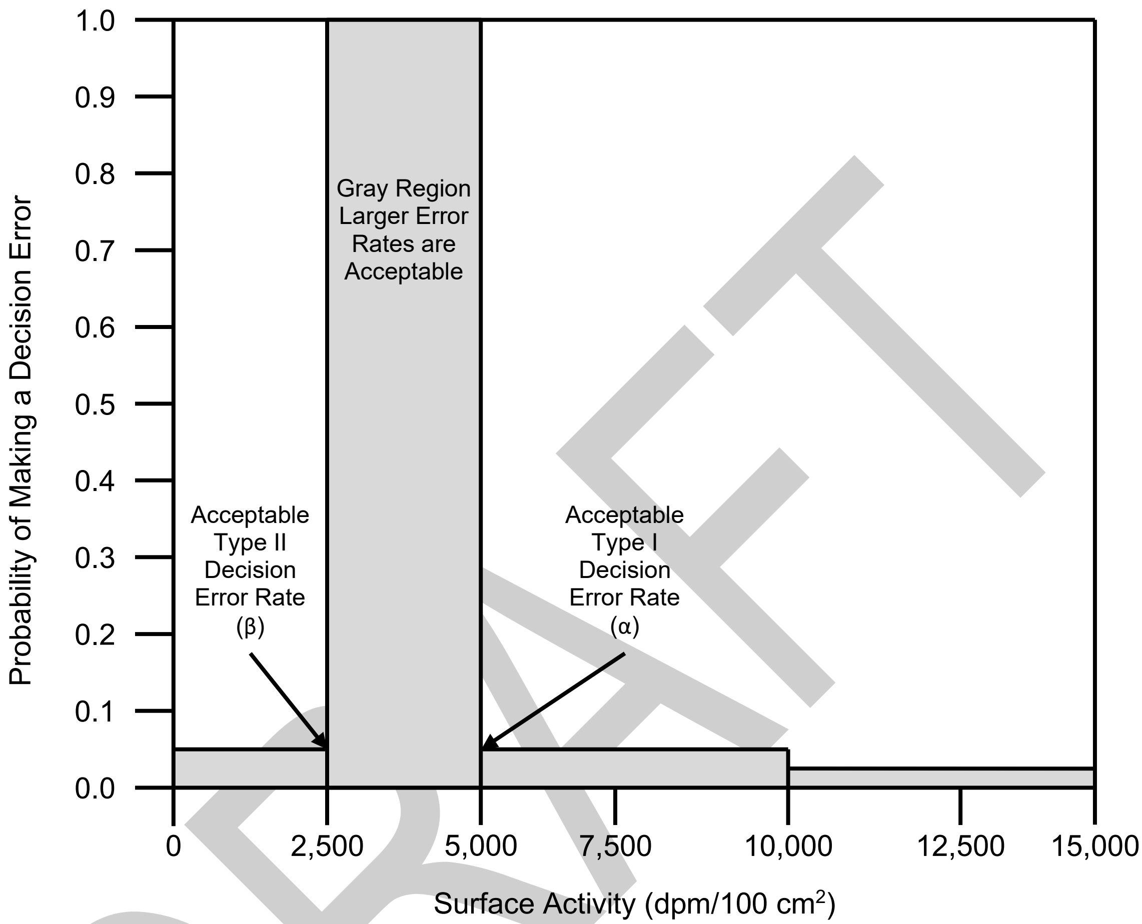


Figure A.1. Decision Performance Goal Diagram for the Class 1 Interior Concrete Survey Unit

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 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:

$$CR_W = DCGL_W \times A \times \varepsilon \quad \text{(A-1)}$$

where A is the probe area, and ε is the total (or 4π) efficiency. Substituting the values for the probe area and efficiency gives:

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

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 type of instrument and method were used to perform measurements in each area.

The Lower Bound of the Gray Region (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 O-1** in **Appendix O**:

$$N = \frac{\left(Z_{1-\alpha} + Z_{1-\beta}\right)^2}{3(P_r - 0.5)^2} \quad \text{(A-1)}$$

From **Table O.2** in **Appendix O**, 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.5** is 4,100 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 deviation 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 O.1** in **Appendix O**, the value of P_r is approximately 1.000.

The number of data points for the WRS test of each combination of reference area and survey units according to the allocation formula was:

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

Adding an additional 20 percent and rounding up yielded 18 data points total for the reference area and each survey unit combined. Note that the same result is obtained by simply using **Table 5.2** or **Table I.3** with $\alpha = \beta = 0.05$ and $\Delta/\sigma = 4.0$. 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.

A.3.6 Evaluate the Power of the Statistical Tests Against the DQOs

(**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). This prospective power curve is shown in **Figure A.6**. See **Appendix M** for 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. It 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 m² (**Figure A.7**). The distance between measurement locations in these survey units was:

$$L = \sqrt{\frac{A}{0.866 \times n}} = \sqrt{\frac{140 \text{ m}^2}{0.866 \times 9}} = 4.2 \text{ m} \quad \text{(A-1)}$$

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

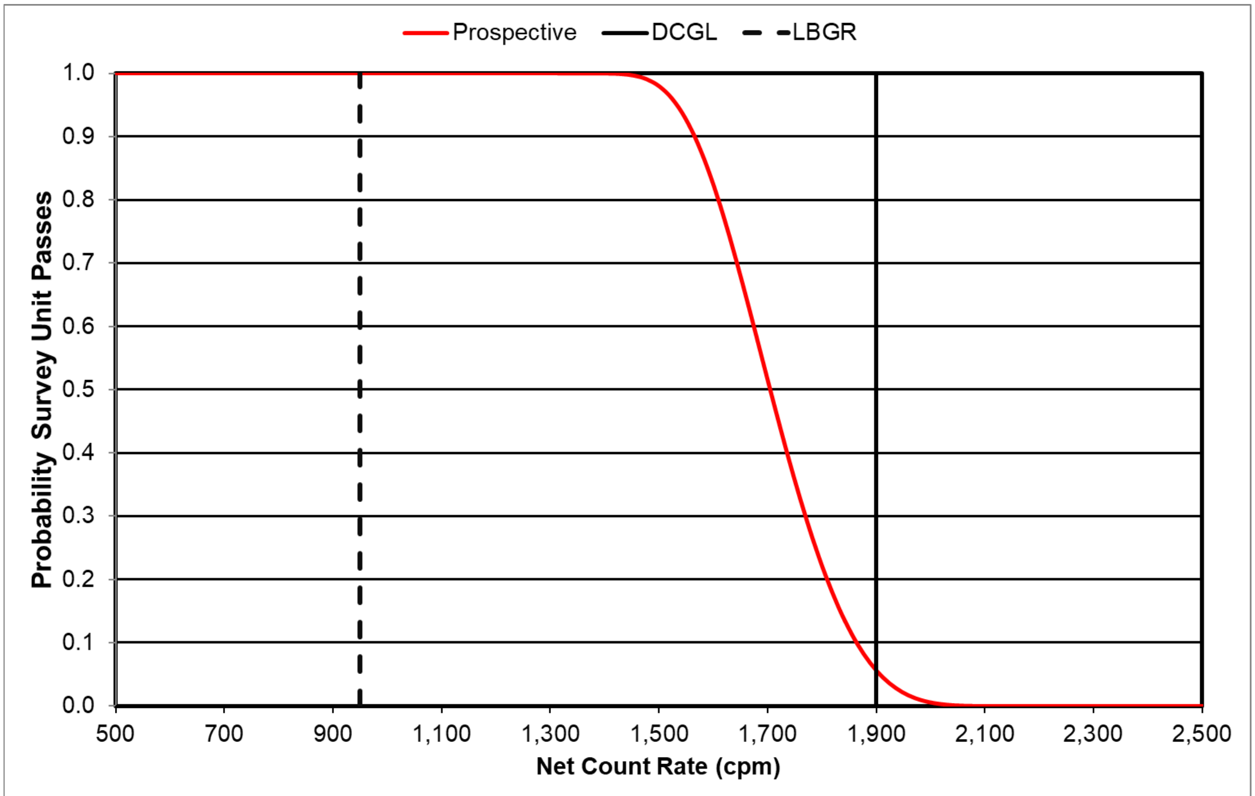


Figure A.1. Prospective Power Curve for the Class 1 Interior Concrete Survey Unit

Appendix A

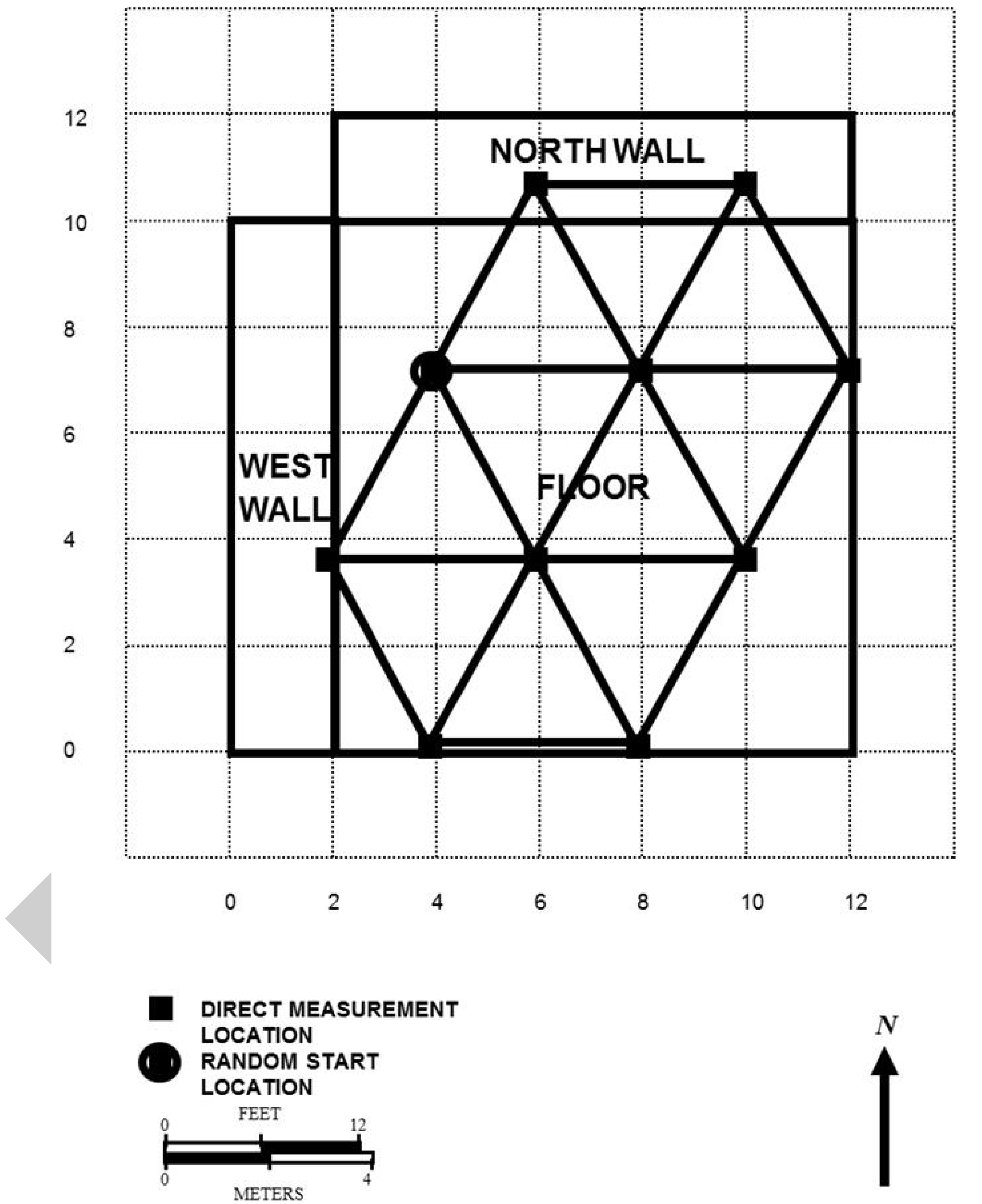


Figure A.2. Measurement Grid for the Class 1 Interior Concrete Survey Unit

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 $0.866L^2 = 13.9 \text{ m}^2$. 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 to account for areas of elevated activity was necessary.

A.3.8 Specify Sampling Locations

(Section 5.3.7)

Two random numbers between zero and one were generated to locate the random start for the sampling grid. Using **Table I.11** in **Appendix I**, 0.322467 and 0.601951 were selected by an unbiased third party. 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:

$$X = 0.322467 \times 12 \text{ m} = 3.9 \text{ m} \quad \text{(A-1)}$$

$$Y = 0.601951 \times 12 \text{ m} = 7.2 \text{ m} \quad \text{(A-2)}$$

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. The measurement grid is shown in **Figure A.7**. When the measurement grid was constructed, it was found that 10 measurement locations were identified within the boundaries of the survey unit, which is greater than the nine 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 4.8.8**)

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 into a Quality Assurance Project Plan

(**Appendix D**)

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

A.4 Conducting Surveys

A.4.1 Perform Reference (Background) Area 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 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**)

The data from the one Class 1 interior concrete survey unit and its associated reference area are given in **Table A.1**. Because 10 sampling locations were identified, 10 results are listed for the survey unit.[4] The average 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 (see **Appendix L.1**) for the data appear in **Table A.2**. They indicate that the data distributions are unimodal with no notable asymmetry. There are two noticeably extreme values in the survey unit data set, at 1,784 and 2,584 cpm. These are both about 2 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 (Q-Q) plot of these data, shown in **Figure A.8**, is consistent with these conclusions. See **Section L.2** of **Appendix L** for instructions on making Q-Q plots. The median and spread of the survey unit data are clearly above those in 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 data set.

[4] 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.

Table A.1. Class 1 interior concrete survey unit and reference area data

	Reference Area (cpm)	Survey Unit (cpm)
	284	2,174
	227	2,197
	202	2,150
	359	2,067
	290	2,244
	378	2,209
	246	1,784
	284	2,303
	334	2,504
	265	2,221
Sample Mean	287	2,185
Sample Standard Deviation	56	182
Sample Median	284	2,203

Abbreviations: cpm = counts per minute

Table A.2. Stem and leaf displays for Class 1 interior concrete survey units

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				

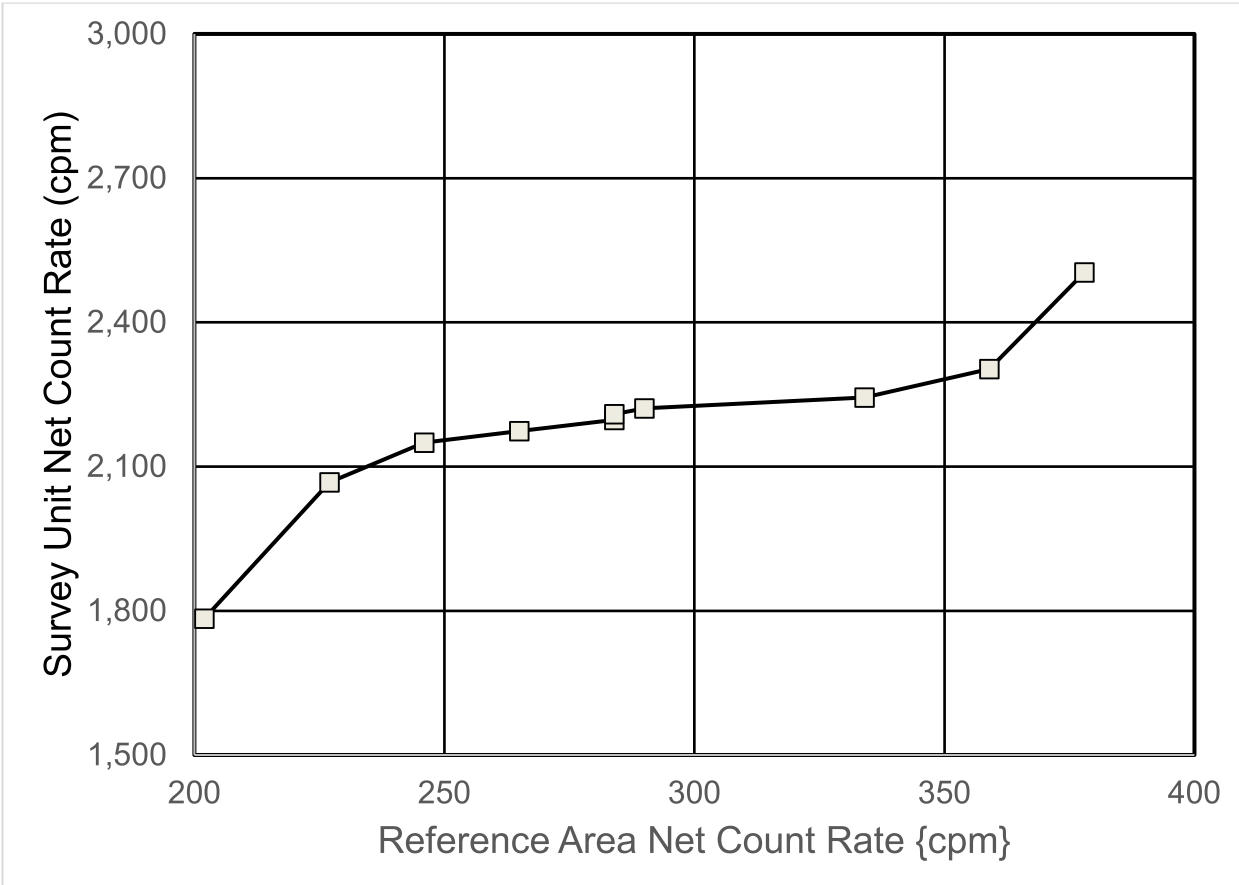


Figure A.1. Quantile-Quantile Plot for the Class 1 Interior Concrete Survey Unit

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 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, there were no survey unit measurements exceeding this value. All of the survey unit measurements exceed the DCGL$_W$, and six exceed 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.3 shows the results of the twenty 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 Adjusted Data 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 of the ranks 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.5** 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, 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 ofΔ/σ were converted to a corresponding count rate, CR, in cpm using:

$$\mathrm{CR} = \mathrm{CR_W} - ({}^{\Delta}/_{\sigma})s \qquad \text{(A-1)}$$

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

The results for this example are plotted in **Figure A.9**, 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 Class 1 interior survey unit failed not because the statistical test lacked sufficient power to reject the null

Table A.1. Wilcoxon Rank Sum 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
2,422	S	1,784	1	0
2,445	S	2,067	2	0
2,398	S	2,150	6	0
2,315	S	2,174	8	0
2,492	S	2,197	12	0
2,457	S	2,209	13	0
2,032	S	2,221	14	0
2,552	S	2,244	16	0
2,752	S	2,303	19	0
2,469	S	2,504	20	0
Sum =			210	99

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

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 is 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 $DCGL_W$.

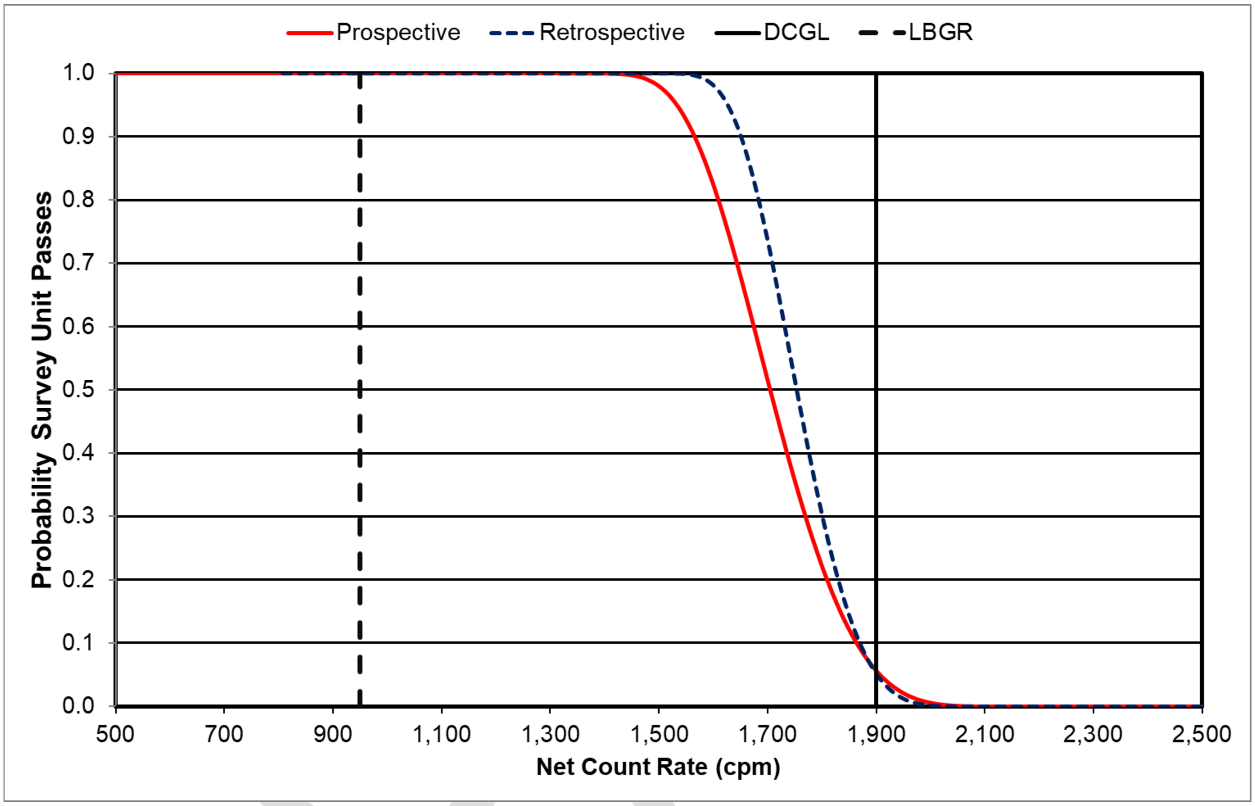


Figure A.1. Retrospective and Prospective Power Curves for the Class 1 Interior Concrete Survey Unit

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

A large number of users of radioactive materials may use 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 non-leaking, 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 provide the regulatory authority with a minimum of—

- 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 Form NRC-314 (Certification of Disposition of Materials)

This minimum information may be used by the regulatory authority to document protection of both the 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[i] document from process knowledge and the nature of the use that either no or unmeasurable quantities of radioactive material remain onsite—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 following information should be included in the FSS report:

- basis for selecting the instrumentation used for the survey
- nature of the radionuclides surveyed
- measurement techniques and instruments used, including references for procedures and protocols used to perform the measurements

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

- minimum detectable concentrations and required measurement method 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. If all measurements are less than the wide-area DCGL (DCGLW), then the statistics do not need to be addressed because the conclusions are obvious. If the mean of the measurements exceeds the DCGLW, 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)/m2 (decays per minute [dpm]/100 square centimeters [cm2], picocuries [pCi]/100 cm2) (removable and/or fixed) for surfaces
    - Bq/liter (L) (pCi/milliliter [mL] or pCi/L) for water
    - Bq/kilogram (kg) (pCi/gram [g]) for solids such as soils or concrete

[i] 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.

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

C.1 EPA Statutory Authorities

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 (OAR) administers several statutes and implementing regulations:

- Clean Air Act (CAA) as amended in 1990, 42 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 Act.
    - National Emissions Standards for Hazardous Air Pollutants (NESHAPS) for Radionuclides, United States Code of Federal Regulations (CFR) Title 40 Part 61.
- Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978, 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 Nuclear Regulatory Commission (NRC) and U.S. Department of Energy (DOE) implement standards under this Act. Both 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.
    - Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings, 40 CFR Part 192.
- Atomic Energy Act (AEA) of 1954, 42 U.S.C. §§ 2011-2296: The AEA requires the management, processing, and utilization of radioactive materials in a manner that protects public health and the environment. EPA, NRC, and DOE are assigned specific sections and authorities under the Act. In some cases, 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, 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,

[1] The user of this manual 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.

given that EPA possesses the authority to promulgate generally applicable radiation protection standards under Reorganization Plan No. 3. For example, under AEA authority EPA promulgated its environmental radiation protection standards for nuclear power operations in 40 CFR Part 190.

- Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear, High-Level and Transuranic Radioactive Wastes (40 CFR 191).

- Nuclear Waste Policy Act (NWPA) of 1982, 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.

- Low Level Radioactive Waste Policy Act (LLRWPA) of 1980, 42 U.S.C. § 2021b: LLRWPA assigns States responsibility for ensuring adequate disposal capacity for low-level radioactive waste generated within their borders.

- Indoor Radon Abatement Act of 1988, 15 U.S.C. § 2601 §§ 301-311.

C.1.2 The Office of Land and Emergency Management

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

- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, 42 U.S.C. §§ 9601-9675: CERCLA, commonly known as Superfund, authorizes EPA, consistent with the National Oil and Hazardous Substances Contingency Plan (NCP, 40 CFR Part 300) 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, the Toxic Substances Control Act, and the Resource Conservation and Recovery Act. Because the CAA designated radionuclides as a hazardous air pollutant, the provisions of CERCLA apply to radionuclides.

- Resource Conservation and Recovery Act (RCRA) of 1976, 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 and accelerator produced radioactive materials and mixed wastes (RCRA waste and AEA materials comingled), however, are not excluded.

C.1.3 The Office of Water

The Office of Water (OW) administers several statutes and implementing regulations:

- Safe Drinking Water Act (SDWA) of 1974, 42 U.S.C. §§ 300f-300j-26: 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 Act.

  - Maximum Contaminant Levels (includes certain radionuclides) (40 CFR 141.11-141.16).

- Clean Water Act (CWA) as amended in 1972, 33 U.S.C. §§ 1251-1387. The CWA 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 (OSCPP) administers the Toxic Substances Control Act:

- Toxic Substances Control Act (TSCA) of 1976, 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 and accelerator produced radionuclides are not excluded.

C.2 DOE Regulations and Requirements

C.2.1 Authorities of the Department of Energy

The Department of Energy Organization Act of 1977, which created the Department of Energy (DOE), the Energy Reorganization Act of 1974, which created the Energy Research and Development Administration, and the Atomic Energy Act of 1954[2] provide the basic authorities of the DOE. The principal DOE statutory authorities and requirements that pertain to radiation protection are shown in **Table C.1.** 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 Atomic Energy Act of 1954 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. (Prior to 1954, all source, byproduct, and special nuclear materials were government owned.) The Atomic Energy Commission (AEC) was given both the regulatory authorities and the mission to develop both the peaceful and military uses of

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

atomic energy. The Act also retained the AEC as the civilian agency responsible for weapons programs production, development and research consistent with the Atomic Energy Act of 1946.

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

<table>
<tr><th>Statutes</th><th>DOE Orders</th></tr>
<tr><td>Atomic Energy Act of 1954, as amended
Energy Reorganization Act of 1974
Uranium Mill Tailings Radiation Control Act of 1978, as amended
Nuclear Non-Proliferation Act of 1978
Department of Energy Organization Act of 1977
West Valley Demonstration Project Act of 1980
Nuclear Waste Policy Act of 1982
Low-Level Radioactive Waste Policy Act of 1980
Low-Level Radioactive Waste Policy Amendments Act of 1985
Energy Policy Act of 1992
Waste Isolation Pilot Plant Land Withdrawal Act of 1992
Price-Anderson Amendments Act of 1988</td><td rowspan="5">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 420.2C, “Safety of Accelerator Facilities”
DOE Order 231.1B, “Environment, Safety and Health Reporting”
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 Materials Packaging Manual”
DOE Order 450.2, “Integrated Safety Management”
DOE Order 451.1B, “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 460.1C, “Packaging and Transportation Safety”
DOE Order 460.2A, “Departmental Materials Transportation and Packaging Management”</td></tr>
<tr><th>DOE Regulations</th></tr>
<tr><td>10 CFR Part 830, “Nuclear Safety Management”
10 CFR Part 835, “Occupational Radiation Protection”
10 CFR Part 851, “Worker Safety and Health Program”</td></tr>
<tr><th>Executive Orders</th></tr>
<tr><td>Executive Order 12580</td></tr>
</table>

Under the Act, 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.

C.2.1.2 Energy Reorganization Act of 1974 (Public Law 93-438 [1974]), as amended

The Energy Reorganization Act of 1974 divided the former AEC and created the Energy Research and Development Administration (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. ERDA was abolished with the creation of DOE in 1977.

C.2.1.3 Department of Energy Organization Act of 1977 Public Law 95-91

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

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 Act, 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. 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, DOE began converting its health and safety Orders to promulgated regulations.

C.2.1.4 Uranium Mill Tailings Radiation Control Act of 1978, as amended

The Uranium Mill Tailings Radiation Control Act (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.2.1.5 West Valley Demonstration Project Act of 1980

This act authorized DOE to carry out a project at West Valley, NY, 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, DOE and its contractors have completed significant work at the site, including successful vitrification (solidification) and storage of high level radioactive waste.

C.2.1.6 Low-Level Radioactive Waste Policy Act of 1980

This act 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 DOE or Federal research and development activities, and authorized States to enter into compacts to carry out this policy. DOE was required to take actions to assist the States in carrying out this policy.

C.2.1.7 Nuclear Waste Policy Act of 1982 (Public Law 97-425, 1983)

This act gives 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 DOE.

C.2.1.8 Low-Level Radioactive Waste Policy Amendments Act of 1985

This act amends the Low-Level 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 DOE to provide financial and technical assistance to the States in carrying out the Act.

C.2.1.9 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:

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

C.2.1.10 Price-Anderson Amendments Act of 1988

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

C.2.2 Executive Orders

Executive Order (E.O.) 12580 delegates to various Federal officials the responsibilities vested in the President for implementing the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA).

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 contained in Part 835 are generally similar to those in DOE Order 5480.11 and those used in NRC Regulations pertaining to the commercial nuclear industry. In addition to the rule, DOE issued a dozen implementation guides, including the "DOE Radiological Control Manual," and other supporting documents.

C.2.3.2 DOE Order 458.1 "Radiation Protection of the Public and the Environment"

This Order, issued in February 2011, contains DOE's requirements for ensuring the protection of the public from the hazards of radiation. This regulation includes dose limits for protection of the public and environment, plus requirements:

1) to apply the As Low As Reasonably Achievable (ALARA) process—to reduce doses to the public as far below the release criterion as is practicable
2) to apply the best available control technology to liquid effluents
3) for control of property containing residual radioactive material
4) for updating DOE's radiation protection requirements for use of the International Commission on Radiological Protection (ICRP) 60 dosimetry, consistent with other DOE radiation protection requirements

DOE O 458.1 is supported by numerous guidance documents, including those listed in this section.

DOE O 458.1 is the primary directive relating to the release of property subject to radiological contamination by DOE operations.

Under DOE O 458.1 and the relevant guidance, DOE established requirements for a case-by-case review and approval for release of real or non-real property containing residual radioactive material. Authorized limits and measurement procedures must be developed by DOE before facilities can release property from their control. The principle requirement is to reduce doses to levels that are as low as practicable using the ALARA process and assuming realistic but conservative use scenarios that are not likely to underestimate dose. This requirement ensures that doses are as far below the primary dose limit of 1 mSv/y (100 mrem/y) as is reasonably achievable. Because the primary dose limit is for doses from all sources and pathways, authorized limits should be selected at levels below a DOE dose constraint of 0.25 mSv/y (25 mrem/y) for real property. However, the goal is to reduce doses under likely-use scenarios to a few fractions of a millisievert per year or less.

In addition to the requirement to apply ALARA and the dose constraint, DOE also utilizes surface contamination guidelines similar to those in NRC Regulatory Guide 1.86 and the 40 CFR Part 192 soil concentration limits for radium and thorium. The ALARA requirement ensures that the 40 CFR Part 192 limits are used appropriately. DOE also permits revision of authorized limits for situations where cleanups to authorized limits are not practicable or where the scenarios used to develop the authorized limits are not appropriate. DOE O 458.1 permits the release of property for restricted use and requires procedures to ensure these restrictions are maintained.

Most DOE remedial action and restoration activities are also subject to CERCLA. In such cases, DOE requirements are integrated into the CERCLA process.

The following sections describe the scope and importance of several guidance documents.

<u>Residual Radioactive Material Control</u>

ANL/EAD/03-1, User's Manual for RESRAD-BUILD Version 3, Argonne National Laboratory, June 2003.

ANL/EAD-3, RESRAD-RECYCLE: A Computer Model for Analyzing the Radiological Doses and Risks Resulting from the Recycling of Radioactive Scrap Metal and the Reuse of Surface-Contaminated Material and Equipment, Argonne National Laboratory, November 2000.

ANL/EAD-4, “User’s Manual for RESRAD Version 7.2”, published by Argonne National Laboratory (ANL) and prepared by ANL and DOE staff, July 2001.

ANL/EAIS/TM-103, “A Compilation of Radionuclide Transfer Factors for Plant, Meat, Milk, and Aquatic Food Pathways and the Suggested Default Values for the RESRAD Code,” Argonne National Laboratory, August 1993.

ANL/EVS/TM/07-1, “User’s Manual for RESRAD-OFFSITE Version 2”, published by Argonne National Laboratory and prepared by ANL, NRC, and DOE staff, June 2007.

ANL/EVS/TM-14/2, “User’s Guide for RESRAD/OFFSITE”, published by Argonne National Laboratory and prepared by ANL, NRC, and DOE staff, March 2018.

ANL/EVS/TM-14/4, “Data Collection Handbook to Support Modeling Impacts of Radioactive Material in Soil and Building Structures,” Argonne National Laboratory, September 2015.

ANL/EVS/TM-18/1, “User’s Guide for RESRAD-ONSITE Code”, published by Argonne National Laboratory and prepared by ANL and DOE staff, March 2018.

DOE/EH-0676, “RESRAD-BIOTA: A Tool for Implementing a Graded Approach to Biota Dose Evaluation,” Department of Energy, January 2004.

DOE-HDBK-1216-2015, “Environmental Radiological Effluent Monitoring and Environmental Surveillance,” Department of Energy, March 2015.

DOE-STD-1153-2019, “A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota,” Department of Energy, February 2019.

PNL-8724, “Radiation Dose Assessments to Support Evaluations of Radiological Control Levels for Recycling or Reuse of Materials and Equipment,” Pacific Northwest Laboratory, July 1995.

<u>ALARA</u>

ANL/EAD/LD-2, “Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0,” Chapters 1 and 5 and App. M, Argonne National Laboratory, September 1993.

DOE HDBK-1215-2014, “Optimizing Radiation Protection of the Public and the Environment for use with DOE O 458.1, ALARA Requirements,” Department of Energy, October 2014.

DOE Order 458.1, “Radiation Protection of the Public and the Environment, Chg. 3,” Department of Energy, January 15, 2013. See subsection 4.d, in particular.

<u>Dose Factors</u>

DOE-STD-1196-2011, “Derived Concentration Technical Standard,” April 2011.

Derived Concentration Standards (DCS) are quantities used in the design and conduct of radiological environmental protection programs at DOE facilities and sites. These quantities represent the concentration of a given radionuclide in either water or air that results in a member of the public receiving 1 mSv (100 mrem) effective dose following continuous exposure for one year for each of the following pathways: ingestion of water, submersion in air, and inhalation.

The purpose of this standard is to establish numerical DCS values reflecting the current state of knowledge and practice in radiation protection. These DCSs are derived using age-specific effective dose coefficients for Reference Persons of the public and age- and gender- dependent intake rates for ingestion of water and inhalation of air. The members of the public are represented by six age subgroups (newborn, 1-year, 5-year, 10-year, 15-year, and adult). The analysis weights the effective dose coefficients for each subgroup by their fractional representation in the United States population and their intake of the radionuclide through inhalation, ingestion, or air submersion. The single-value nature of the resultant DCSs enables them to be effectively and consistently applied in radiological environmental protection programs at DOE facilities and sites.

DOE Order 435.1, "Radioactive Waste Management"

DOE Order 435.1 establishes the policies, guidelines, and requirements by which DOE manages its radioactive and mixed waste and contaminated facilities. The order implements DOE's responsibilities and authorities for protection of public and worker health and safety and the environment under the Atomic Energy Act. It contains the requirements for management and disposal of low-level waste, including waste from the decommissioning of radioactively contaminated facilities.

The order specifies performance objectives to assure that external exposure waste concentrations of radioactive material—which may be released into surface water, ground water, soil, plants, and animals—result in an effective dose equivalent that does not exceed 0.25 mSv/y (25 mrem/y) to a member of the public. Releases to the atmosphere shall meet the requirements of CFR Title 40 Part 61. Reasonable efforts should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable. Radiological performance assessments are required for the disposal of waste for the purpose of demonstrating compliance with these performance objectives.

For low-level waste, there also are requirements on waste generation, waste characterization, waste acceptance criteria, waste treatment, and long-term storage. The order includes additional disposal requirements concerning disposal facility and disposal site design and waste characteristic, site selection, facility operations, site closure and post closure, and environmental monitoring.

C.3 NRC Regulations and Requirements

C.3.1 NRC's Mission and Statutory Authority

The mission of the U.S. Nuclear Regulatory Commission (NRC) is to ensure adequate protection of the public health and safety, the common defense and security, and adequate protection of 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; non-power 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 Atomic Energy Act of 1954, as amended, provides the foundation for regulation of the Nation's commercial nuclear power industry.

NRC regulations are issued under CFR Title 10, Chapter I. Principal statutory authorities that govern the NRC's work are:

- Administrative Procedures Act of 1946
- Atomic Energy Act of 1954, as amended
- National Environmental Policy Act of 1970
- Energy Reorganization Act of 1974, as amended
- Uranium Mill Tailings Radiation Control Act of 1978, as amended
- Nuclear Non-Proliferation Act of 1978
- 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
- Diplomatic Security and Anti-Terrorism 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 of the survey manual 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 be applicable at NRC-licensed sites at the time of decommissioning.

NRC's requirements for decommissioning and license termination are contained in 10 CFR 30.36, 40.42, 50.82, 70.38, and 72.54. The "Radiological Criteria for License Termination," also known as the License Termination Rule (LTR), are found in Subpart E to 10 CFR Part 20. Within the LTR, criteria for both unrestricted and restricted release are provided. According to 10 CFR 20.1402, 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 (TEDE) to an average member of the critical group that does not exceed 0.25 mSv (25 mrem) per year, including that from groundwater sources of drinking water, and the residual radioactivity has been reduced to ALARA levels. Determination of the levels that are ALARA must take into account consideration of any detriments, such as deaths from transportation accidents, expected to potentially result from decontamination and waste disposal. The criteria for license termination with restrictions on future land use are described in 10 CFR 20.1403. Under certain conditions, the restricted release criteria allow a limit of 0.25 mSv/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.

Other documents that were used in the past and that may continue to have some applicability in special cases include “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” (10 CFR Part 40, Appendix A) and “Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings” (40 CFR Part 192, Subparts D and E). These regulations, issued by the NRC and 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 requires 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 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 contained 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. Radiological surveys also may be performed by the NRC at sites where there is not a license.

The NRC decommissioning process for a site requiring substantial remediation can be described by the activities listed below:

- licensee notifies the NRC they intend 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 decommissioning plan or license termination plan
- NRC review and approval of decommissioning plan or license termination plan
- performance of decommissioning actions described in the plan
- performance of final status survey and submittal of final status survey report
- NRC performance and documentation of confirmatory survey
- NRC termination of license

The NRC staff plans to use the information contained in this manual as primary guidance for conducting radiological surveys of routine licensee requests for license termination and non-routine license termination requests that require more extensive decommissioning actions. Supplementary guidance may be used by the NRC staff to assist licensees in conducting such surveys or aid the NRC staff in evaluating licensee's 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 DOD Regulations and Requirements

The 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 DOD.

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

C.4.1 Authorities of the Department of Defense

The Military Application of Atomic Energy Authority, Sec. 91b of the Atomic Energy Act of 1954, as amended, provides authority for the President to direct the Atomic Energy Commission to authorize the DoD (to include the separate military services) to acquire specified quantities of special nuclear material and utilization facilities for military purposes.

Additionally, in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, DoD (to include its separate military services) is 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 the 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

DOD's list of radioactive materials includes:

- 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 (NORM) or accelerator-produced radioactive material (NARM), such as radium, and not classified as source material
- materials containing induced or deposited radioactivity

Ionizing radiation producing devices are electronic devices capable of emitting ionizing radiation. Examples are 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 radioactivity or induced radioactivity 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.

Radioactive material 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 NARM may be used under a Department of the Army Radioactive Material Authorization (DARA) issued by the Army Materiel Command (AMC) 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 United States Air Force, the United States Army, and the United States Navy possess radioactive materials under Section 91b, Chapter 9, Military Application of Atomic Energy, Atomic Energy Act of 1954 (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 Atomic Energy Act. Each military service 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

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 DOD.

DOD and each military service 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 Concerning Development of Environmental Radiological Surveys

Regulations and Requirements Concerning Development of Environmental Radiological Surveys:

- DOD Instruction 4715.23, Integrated Recycling and Solid Waste Management (October 2016)
- DOD Directive 4715.1E, Environment, Safety, and Occupational Health (March 2005)
- DOD Instruction 4715.05, Environmental Compliance at Installations Outside of the United States, Incorporating Change 2 (August 2018)

Regulations and Requirements Concerning Use of Radioactive Sources and Development of Occupational Health Programs and Radiation Protection Programs:

- DOD 6055.5-M, Occupational Medical Examinations and Surveillance Manual, Incorporating Change 3 (August 2018)
- DOD Instruction 6055.08, Occupational Ionizing Radiation Protection Program, Incorporating Change 2 (August 2018)

Examples of Air Force Instructions (AFIs):

- AFMAN 40-201, Radioactive Materials (RAM) Management (March 2019)
- AFI 32-7020, The Environmental Restoration Program, Incorporating Change 1 (April 2016)
- AFI 32-7066, Environmental Baseline and Close-out Surveys in Real Estate Transactions (January 2015)

Examples of Army Regulations (ARs) and Other Requirements:

- AR 385-10, The Army Safety Program (February 2017)
- DA PAM 385-24, The Army Radiation Safety Program (November 2015)
- DA PAM 40-18, Occupational Dosimetry Guidance and Dose Recording for Exposure to Ionizing Radiation (October 2012)
- AR 40-5, Preventive Medicine (May 2007)
- AR 40-10, Health Hazard Assessment Program in Support of the Army Acquisition Process (July 2007)
- AR 200-1, Environmental Protection and Enhancement (December 2007)

- AR 700-48, Management of Equipment Contaminated with Depleted Uranium or Radioactive Commodities (September 2002)
- AR 750-43, Army Test, Measurement, and Diagnostic Equipment (January 2014)
- TB MED 521, Occupational and Environmental Health: Management and Control of Diagnostic, Therapeutic, and Medical Research X-Ray Systems and Facilities (February 2002)
- TB MED 522, Occupational and Environmental Health: Control of Health Hazards from Protective Material Used in Self-Luminous Devices (August 1980)
- TB MED 525, Control of Hazards to Health from Ionizing Radiation Used by the Army Medical Department (March 1988)
- TB 43-180, Calibration and Repair Requirements for the Maintenance of Army Materiel (January 2018)
- TB 43-0108, Handling, Storage and Disposal of Army Aircraft Components Containing Radioactive Materials (February 1979)
- TB 43-0116, Identification of Radioactive Items in the Army (April 1998)
- TB 43-0122, Identification of U.S. Army Communications-Electronics Command Managed Radioactive Items in the Army Supply System (February 1989)
- TB 43-0197, Instructions for Safe Handling, Maintenance, Storage and Transportation of Radioactive Items under License 12-00722-06 (June 2006)
- TB 43-0216, Safety and Hazard Warnings for Operation and Maintenance of TACOM Equipment (October 1990)
- TM 3-261, Handling and Disposal of Unwanted Radioactive Material (May 1988)
- TM 55-315, Transportability Guidance for Safe Transport of Radioactive Materials (June 1989)

Examples of Navy Regulations:

- NAVMED P-5055, Radiation Health Protection Manual, Incorporating Change 1 (April 2018)
- NAVSEA S0420-AA-RAD-010, Revision 2A, Radiological Affairs Support Program (RASP) Manual (May 2019)
- OPNAVINST 6470.3, Navy Radiation Safety Committee (July 2015)
- NAVSEA 5100.18B, Radiological Affairs Support Program (February 2007)
- BUMEDINST 6470.10B, Initial Management of Irradiated or Radioactively Contaminated Personnel (September 2003)

C.5 State and Local Regulations and Requirements

An Agreement State is a state that has signed an agreement with the NRC allowing the State to regulate the use of radioactive materials—that is, specifically Atomic Energy Act materials—within that State. **Table C.2** lists the Agreement States as of June 11, 2019. Each Agreement State provides regulations governing the use of radioactive materials that may relate to radiation site investigations.[3] **Table C.3** lists the states that regulate naturally occurring radioactive material (NORM) as of March 15, 2013. At least one other State is in the process of developing regulations governing the use of NORM. The decision maker should check with the State to ensure compliance with all applicable regulations.

Table C.1 Agreement States as of June 11, 2019

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

Table C.2 States That Regulate Diffuse NORM as of March 15, 2013

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

[3] A current list of Agreement States can be obtained through the U.S. Nuclear Regulatory Commission on the State Program Directory Web page operated by the Oak Ridge National Laboratory at https://scp.nrc.gov/asdirectory.html.

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.[1] The MARSSIM guidance focuses on demonstration of 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/quality control (QA/QC). The goal of a QA/QC program is to identify and implement sampling and analytical methodologies that limit the introduction of error into 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 end 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

[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.

developed based on the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP) (EPA 2005b). The QAPP integrates all technical and quality aspects and defines in detail how specific QA and QC activities will be implemented during the survey (**Section D.2**).

- Data Quality Assessment (DQA) is 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 (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 the quality of the data. Data verification and validation is the process of evaluating the quality of the data collected for a survey to determine if the data is appropriate for use in the assessment process and to make project decisions (**Section D.4**).

Much of this Appendix is written from the perspective of Scenario A, but important considerations for Scenario B are included throughout the Appendix. Details on the project-level components for planning and assessing environmental collection activities are provided in this appendix, as well as **Chapters 2, 3, 4, 5, and 8.** 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 is provided in MARSSIM **Chapters 6 and 7** and **Appendix H.**

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 the 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 assures 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 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).

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 area or 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 and 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 method performance characteristic that is expressed in terms of Data Quality Indicators (DQIs) for precision (indicating random measurement error), bias (indicating systematic measurement error), representativeness and measurement detectability, comparability, and completeness. **Section D.4.2** 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

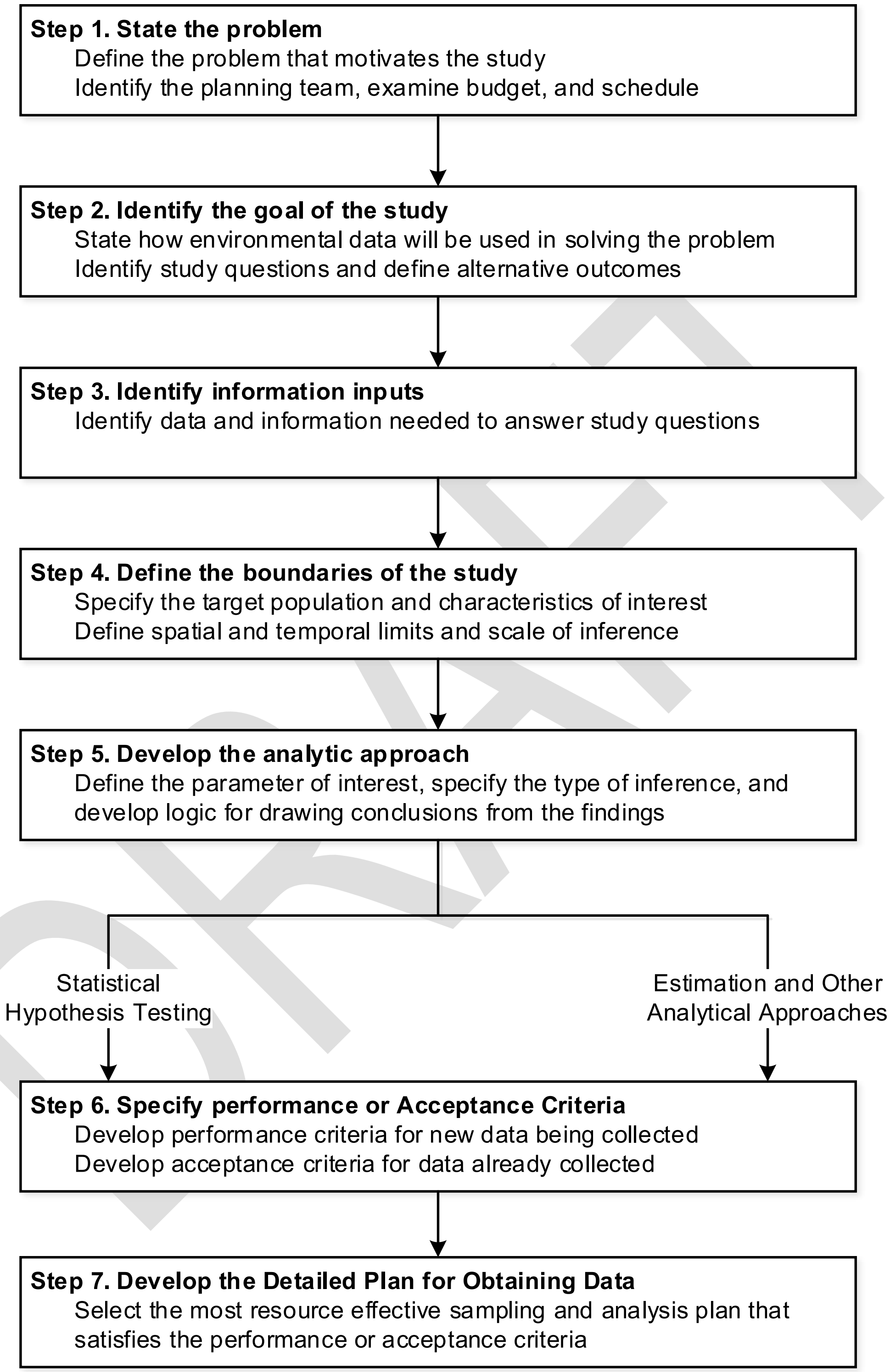


Figure D.1: The Data Quality Objectives Process

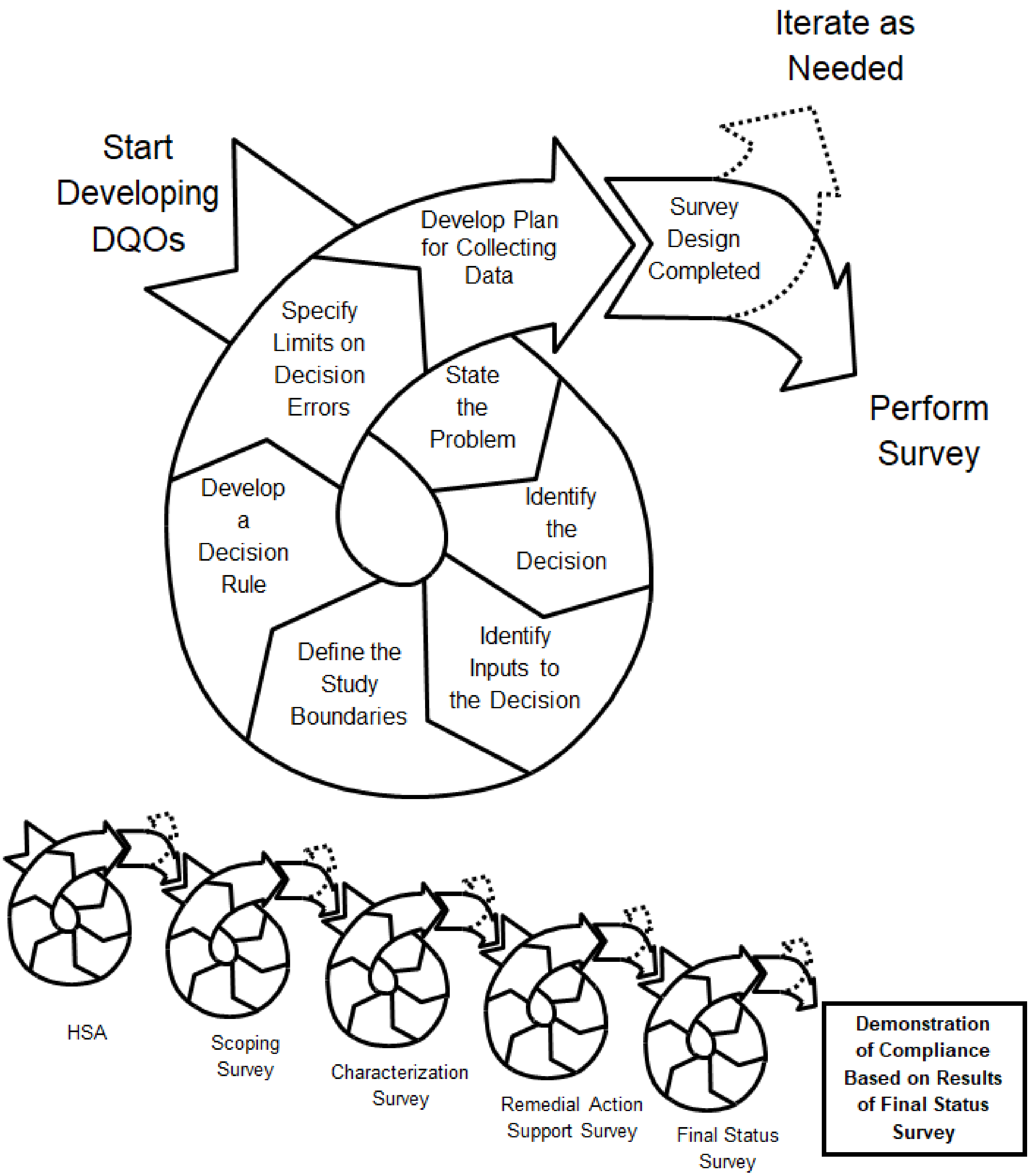


Figure D.2: Repeated Application of the DQO Process throughout the Radiation Survey and Site Investigation Process

- Ruggedness

Section D.1.9 presents additional detail on MQOs.

The DQO process is a flexible planning tool that can be used more or less intensively as the situation requires. For surveys that have multiple decisions, such as characterization 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 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.1.9** provides additional detail on MQOs.

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.

The expected outputs of this step are as follows:

- 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

For an FSS, examples of planning team members and stakeholders are described in **Section 3.2.** 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 goal 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, re-evaluation of the modeling assumptions used to develop the derived concentration guideline levels (DCGLs), reassessment of the survey unit to see if 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. The four key activities for this step are as follows:

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 information are needed to resolve the decision statement.
2. Determine the sources for each item of information. Identify and list the sources for the required information.
3. Identify the information needed to establish the DCGL or AL based on the release criterion. 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. Field and laboratory measurement techniques for radionuclides are discussed in **Chapters 6 and 7.** Information

on using field and laboratory equipment, their detection limits, and analytical costs are listed in **Appendix H.** This performance information will be used in Steps 5 and 7 of the DQO process.

The expected outputs of this step are the following:

- a list of information inputs and sources needed to resolve the decision statement
- 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 whether or not 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 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 represents 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 areas or 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.

The expected outputs of this step are as follow:

- 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 form of the radionuclides should be described. For example, describing the residual radioactive materials in terms of total uranium (U) 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 (^{234}U), uranium-235 (^{235}U), and uranium-238 (^{238}U).

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 (cm). 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 area 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 ground water 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 measurement frequency 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 action level (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 action level of 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 Radiation Survey and Site Investigation 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.

The expected outputs of this step are as follow:

- the radionuclide(s) of interest that characterizes the level of residual radioactive material
- the action level 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 action level is based on long-term, average 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) it 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 where 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 action level is based on long-term, mean 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. Negative attributes include that (1) it will not protect against the effects of extreme values, and (2) it is not a very representative measure of central tendency for highly skewed distributions (EPA 2006b).

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 $DCGL_W$.[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 arithmetic 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 action level 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 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 Wilcoxon Rank Sum (WRS) test is used when the radionuclide appears in background, because measurements are made in both the survey unit and the reference area.

Figure D.3 contains a simple, hypothetical example of a case where the radionuclide does not appear in background. The upper portion of the figure shows a probability distribution of residual radioactive material concentrations in the surface soil of the survey unit. The parameter of interest is the location of the mean of this distribution, represented by the vertical dotted line and denoted by the symbol “D.”

[2] The “W” in $DCGL_W$ historically stood for Wilcoxon Rank Sum 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.”

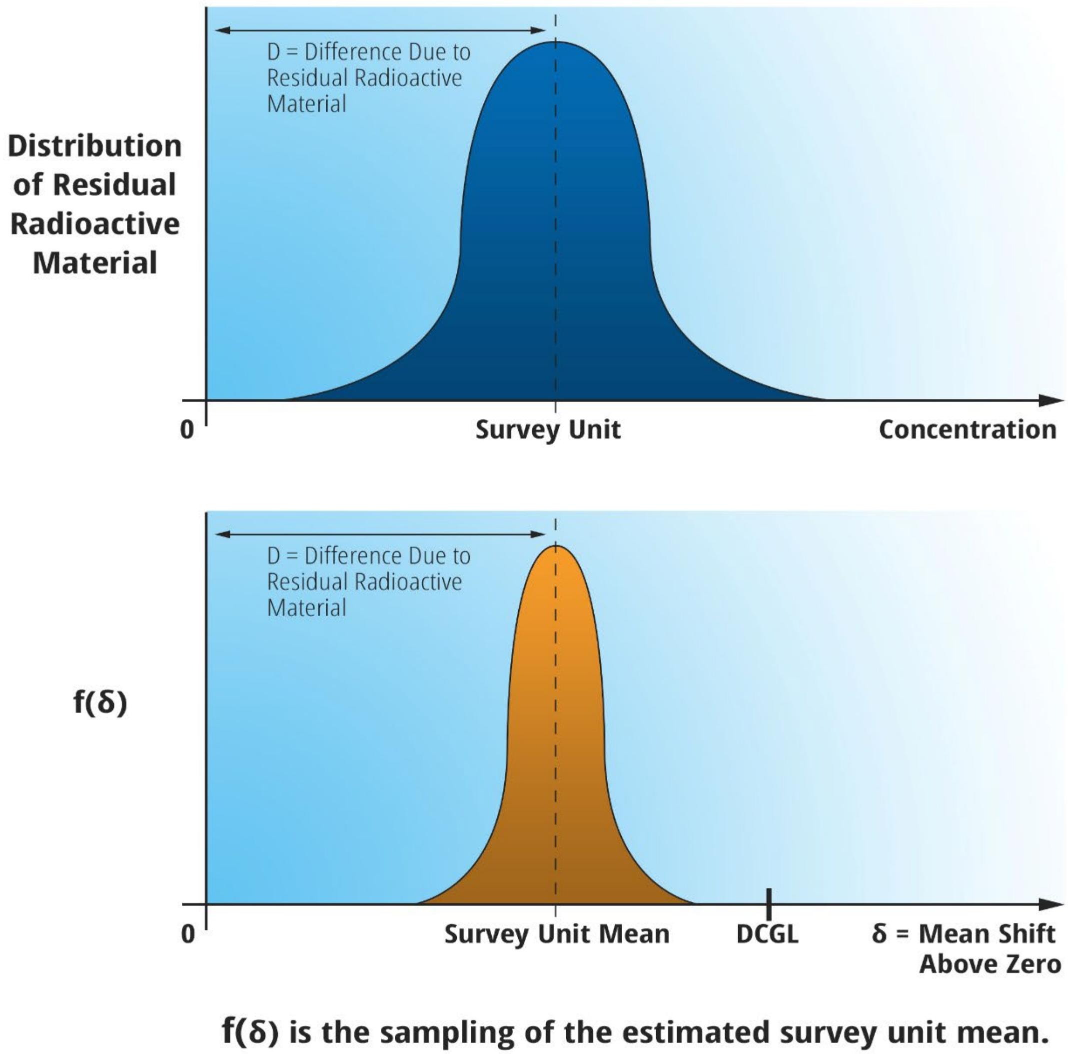


Figure D.3: Example of the Parameter of Interest for the Case Wherein the Radionuclide Does Not Appear in Background

The decision rule for this case is that if the mean concentration in the survey unit is less than the investigation level, then the survey unit is in compliance with the release criteria. To implement the decision rule, an estimate of the mean concentration in the survey unit is required. An estimate of the mean of the survey unit distribution may be obtained by measuring radionuclide concentrations in soil at a set of n randomly selected locations in the survey unit. A point estimate for the survey unit mean is obtained by calculating the simple arithmetic average of the n measurements. Due to measurement variability, there is a distribution of possible values for the point estimate for the survey unit mean, δ. This distribution is referred to as $f(\delta)$ and is shown in the lower graph of **Figure D.3.** The investigation level for the Sign test is the $DCGL_W$, shown on the horizontal axis of the graph.

If $f(\delta)$ lies far to the left or right of the $DCGL_W$, a decision about whether the survey unit demonstrates compliance can be easily made. However, if $f(\delta)$ overlaps the $DCGL_W$, statistical decision rules are used to assist the decision maker. Note that the width of the distribution for the estimated mean may be reduced by increasing the number of measurements. Thus, a large number of samples will reduce the probability of making decision errors.

Figure D.4 shows a simple, hypothetical example of a case where the radionuclide appears in background. The upper portion of the figure shows one probability distribution representing background radionuclide concentrations in the surface soil of the reference area and another probability distribution representing radionuclide concentrations in the surface soil of the survey unit. The graph in the middle portion of the figure shows the distributions of the estimated mean concentrations in the reference area and the survey unit. In this case, the parameter of interest is the difference between the means of these two distributions, D, represented by the distance between the two vertical dotted lines.

The decision rule for this case is that if the difference between the mean concentration in the survey unit and the mean concentration in the reference area is less than the investigation level, then the survey unit is in compliance with the release criteria. To implement the decision rule, an estimate of the difference is required. This estimate may be obtained by measuring radionuclide concentrations at a set of n randomly selected locations in the survey unit and m randomly selected locations in the reference area. A point estimate of the survey unit mean is obtained by calculating the simple arithmetic average of the n measurements in the survey unit. A point estimate of the reference area mean is similarly calculated. A point estimate of the difference between the two means is obtained by subtracting the reference area average from the survey unit average.

The measurement distribution of this difference, $f(\delta)$, is centered at D, the true value of the difference. This distribution is shown in the lower graph of **Figure D.4.** Once again, if $f(\delta)$ lies far to the left (or to the right) of the $DCGL_W$, a decision about whether or not the survey unit demonstrates compliance can be easily made. However, if $f(\delta)$ overlaps the $DCGL_W$, statistical decision rules are used to assist the decision maker

Decision makers determine the requirements of the hypothesis test based on 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.

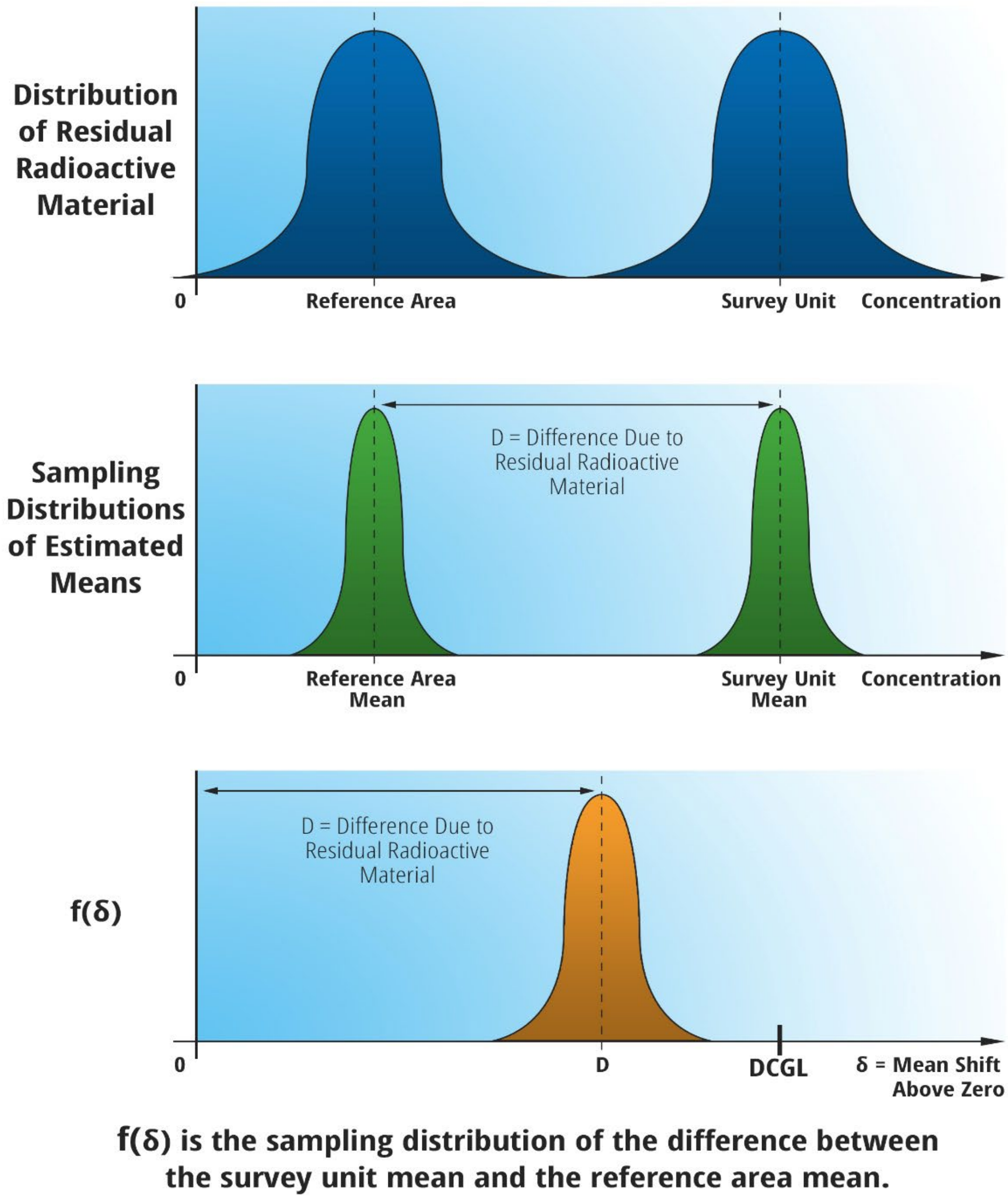


Figure D.4: Example of the Parameter of Interest for the Case wherein the Radionuclide appears in Background

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, 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 et al. 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 by—

Scenario A H_0: X > DCGL versus H_1: X ≤ DCGL

or

Scenario B H_0: X ≤ AL versus H_1: X > 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.

U.S. Environmental Protection Agency (EPA) QA/G-9, Section 1.2 (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 (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 action level 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 action level and, therefore, impossible to design a survey. This makes intuitive sense, as it is impossible to prove that you are below an action level of 0 or 0 above background. When Scenario B is selected, a discrimination limit (DL) is set above the action level as the upper bound of the grey region.

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 number of 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 and/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 criterion will have a higher chance of failing. In Scenario B, inadequate power means that survey units that actually exceed the release criterion will have a higher chance of going undetected. In this case, the survey unit may be released due only to an inadequate number of samples.

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 in Scenario B that a "lazy sampling approach" could lead to false adoption of the null hypothesis and 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 or not 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 error. Sampling design error may be controlled by collecting a large number of samples. Using more precise measurement techniques or field duplicate analyses can reduce measurement error. 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. 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).

There are trade-offs 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 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 where 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 are able to 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, etc.)

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 or not 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 by a table, 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.

Table D.1 Representation of Decision Errors for a Final Status Survey (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 Criterion	There is no decision error.	There is a Type II decision error (β): Incorrectly Fail to Release Survey Unit.
Exceeds Release Criterion	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 criterion.

Table D.2: Representation of Decision Errors for a Final Status Survey 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 Criterion	There is no decision error.	There is a Type II decision error (β): Incorrectly Fail to Release Survey Unit.
Meets Release Criterion	There is a Type I decision error (α): Incorrectly 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 criterion.

A Type II decision error occurs when the null hypothesis is accepted when it is 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.

A similar table may be constructed for Scenario B, as shown in **Table D.2.** Note that 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 criterion. In Scenario B, a lower value of α reduces the probability of failing to release a survey unit that is in compliance with the release criterion. 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 is in compliance with the release criterion. In Scenario B, a lower value of β reduces the probability of incorrectly releasing a survey unit that exceeds the release criterion.

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, LBGR or DL, and the estimated standard deviation of the distribution of the parameter of interest.

There are five activities in **Section D.1.6** that 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 choosing the null hypothesis.

    - Define both types of decision errors (Type I and Type II), and establish the true condition of the survey unit for each decision error.

    - Specify and evaluate the potential consequences of each decision error.

    - Establish which decision error has more severe consequences near the action level. 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 action level. Additional guidance on specifying a gray region is available in EPA QA/G-4, Guidance for the Data Quality Objectives Process (EPA 2006c). In Scenario A, the upper bound of the gray region (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.

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 difference between the survey unit mean concentration of residual radioactive material and the reference area mean concentration in the case where the radionuclide is present in background, or simply the survey unit mean concentration in the case where 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 criterion, 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 or not 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 criterion. This is shown as Scenario A in **Figure D.5.** The null hypothesis is that the survey unit exceeds the release criteria. Using this statement of H_0 means that significant evidence that the survey unit does not exceed the release criterion is required before the survey unit would be released.

For Scenario A (**Figure D.5**), the null hypothesis is that the survey unit does not meet the release criterion. A Type I decision error would result in the release of a survey unit containing residual radioactive material above the release criterion. The probability of making this error is α. Setting a high value for α would result in a higher risk that survey units that might be somewhat in excess of the release criterion would be passed as meeting the release criterion. Setting a low value for α would result in fewer survey units where 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.

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

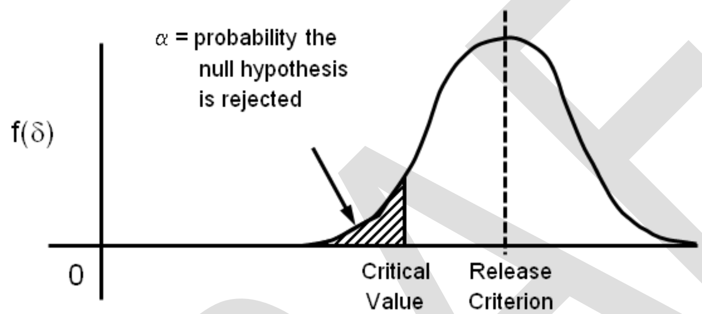
SCENARIO A

Assume as a null hypothesis that the survey unit exceeds the release criterion. This requires significant evidence that the residual radioactivity in the survey unit is less than the release criterion to reject the null hypothesis (and pass the survey unit). If the evidence is not significant at level α, the null hypothesis of a non-complying survey unit is accepted (and the survey unit fails).

HYPOTHESIS TEST

H_0 : Survey Unit does not meet the Release Criterion
H_a : Survey Unit does meet the Release Criterion

Survey unit passes if and only if the test statistic falls in the rejection region.



This test directly addresses the compliance question.

The mean shift for the survey unit must be significantly below the release criterion for the null hypothesis to be rejected.

With this test, site owners face a trade-off between additional sampling costs and unnecessary remediation costs. 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) for survey units at or near background levels.

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

A high percentage of survey units slightly below the release criterion may fail the release criterion, 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 criterion will not be improperly released.

Figure D.5: Statement of the Null Hypothesis for the Final Status Survey Addressing the Issue of Compliance

For Scenario B (**Figure D.6**), the null hypothesis is that the survey unit meets the release criterion. A Type I decision error would result in failing to release a survey unit that does not contain residual radioactive material above the release criterion. The probability of making this error is α. Setting a high value for α would result in a higher likelihood that survey units might be somewhat below the release criterion and still fail to meet the release criterion. Setting a low value for α would result in fewer survey units where the null hypothesis is rejected. 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.

More information on Scenario B can be found in the NRC draft report NUREG-1505, *A Proposed Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys (Revision 1, Final)* (NRC 1998).

For Scenario A, the alternative hypothesis is that the survey unit does meet the release criterion. A Type II decision error would result in either unnecessary costs due to remediation of survey units that are truly below the release criterion 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 criterion 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 criterion. A Type II decision error would result in releasing a survey unit that has residual radioactive material above the release criterion. 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 criterion 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 criterion, 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 earlier, 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:

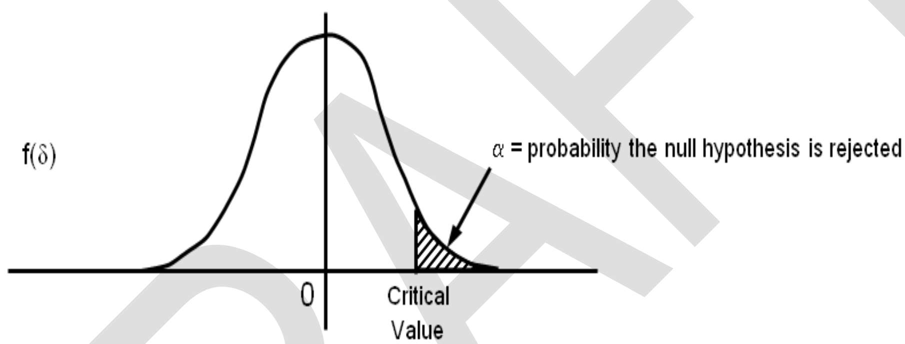
SCENARIO B

Assume as a null hypothesis that the survey unit is indistinguishable from background. 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).

HYPOTHESIS TEST

H_0 : Survey Unit is Indistinguishable from Background
H_a : Survey Unit is Distinguishable from Background

Survey unit passes if and only if the test statistic falls in the rejection region.



Distinguishability from background may be of primary importance to some stakeholders.

The residual radioactivity in the survey unit must be significantly above background for the null hypothesis to be rejected.

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

A high percentage of survey units slightly below the release criterion will fail unless large numbers of measurements are used. This is necessary to achieve a high degree of assurance that for most sites at or above the release criterion the null hypothesis will fail to be improperly released.

Figure D.6: Statement of the Null Hypothesis for the Final Status Survey Addressing the Issue of Indistinguishability from Background Using Scenario B

- In radiation protection practice, public health risk is modeled as a linear function of dose (BEIR 1990). Therefore, a 10 percent change in dose, say 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, one would prospectively address as part of the DQO process 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) and in Scenario B (α) is the risk of requiring additional remediation when a survey unit already meets the release criterion.

- Unlike the health risk, the cost associated with this type of error may be highly nonlinear. The costs will depend on whether the survey unit has already had remediation work performed on it 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 criterion 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 criterion. 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 actually 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 also have 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 demonstrating indistinguishability of the survey unit concentrations 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 (see **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 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 where 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, moisture, and others—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 data quality assessment, then the increased relative uncertainty of the measurement process must be accounted for during the planning stage to prevent loss of statistical power. **Appendix N** provides three examples that illustrate the differences that might be expected between the prospective and data quality assessment (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 $\frac{N}{2}$ 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 Δ/σ values between 1 and 3. The number of samples needed rises dramatically when Δ/σ is smaller than 1. Conversely, little is usually gained by making Δ/σ larger than about 3. It is important, however, that overly optimistic estimates for σ be avoided. 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**).

Thus, the $DCGL_{EMC}$ used for the Elevated Measurement Comparison (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 via 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 via external exposure. The exact relationship between the $DCGL_{EMC}$ and the $DCGL_W$ is a complicated function of the dose or risk modeling pathways, but area factors that relate the two DCGLs can be tabulated for most radionuclides (**Chapter 5**), and site-specific area factors can also be developed.

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. Where 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 (and the resulting area factor is large enough) that $DCGL_{EMC}$ can be detected by scanning. The details of this process are discussed in **Chapter 5.** For some radionuclides (e.g., hydrogen-3 [^{3}H]) 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.7** shows the probability of sampling a circular area of size A with either a square or triangular sampling pattern. The ELIPGRID-PC (Davidson 1995) computer code can also be used to calculate these probabilities.

In this part of the DQO process, the concern is 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 prior to 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, an evaluation of the survey objectives and considerations can be performed. 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.

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 does not meet the release criterion. An example of such a chart, referred to as a power chart, is shown in **Figure D.8.** In this example, α is 0.025 and β is 0.05, providing an expected power $(1-\beta)$ of 0.95 for the test.

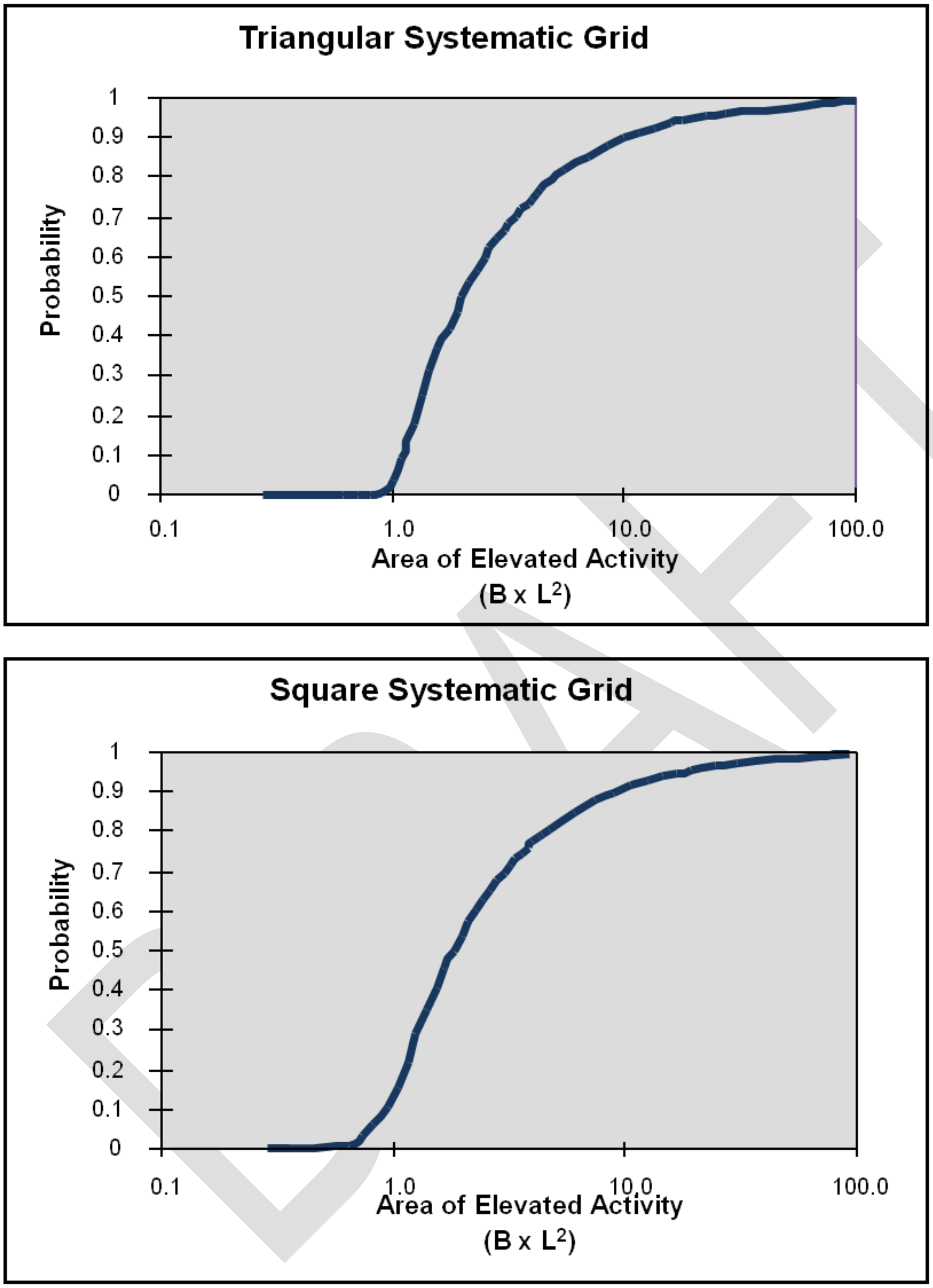


Figure D.7: Geometric Probability of Sampling At Least One Point of an Area of Elevated Activity as a Function of Sample Density with Either a Triangular or Square Sampling Pattern

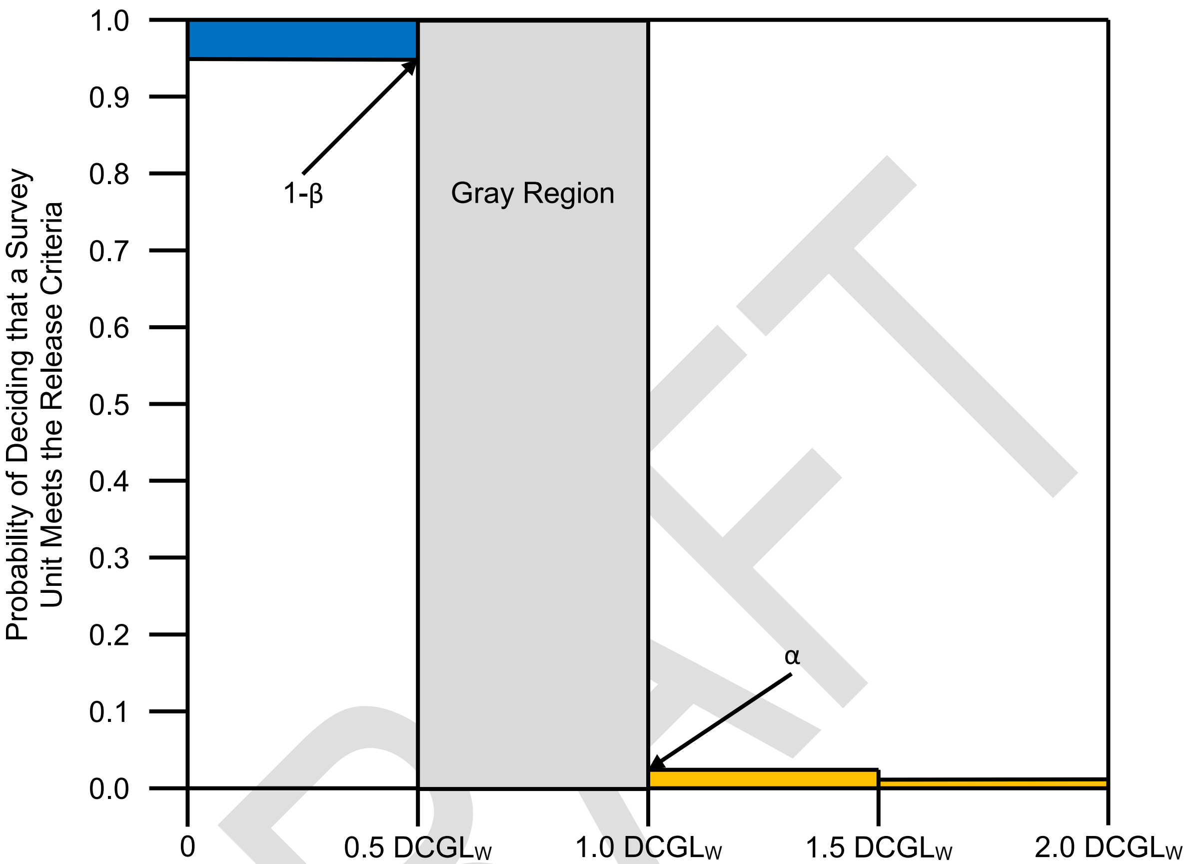


Figure D.8: Example of a Scenario A Power Chart Illustrating the Decision Rule for the Final Status Survey

A second method for presenting the information is shown in **Figure D.9.** 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. It is clear that 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.

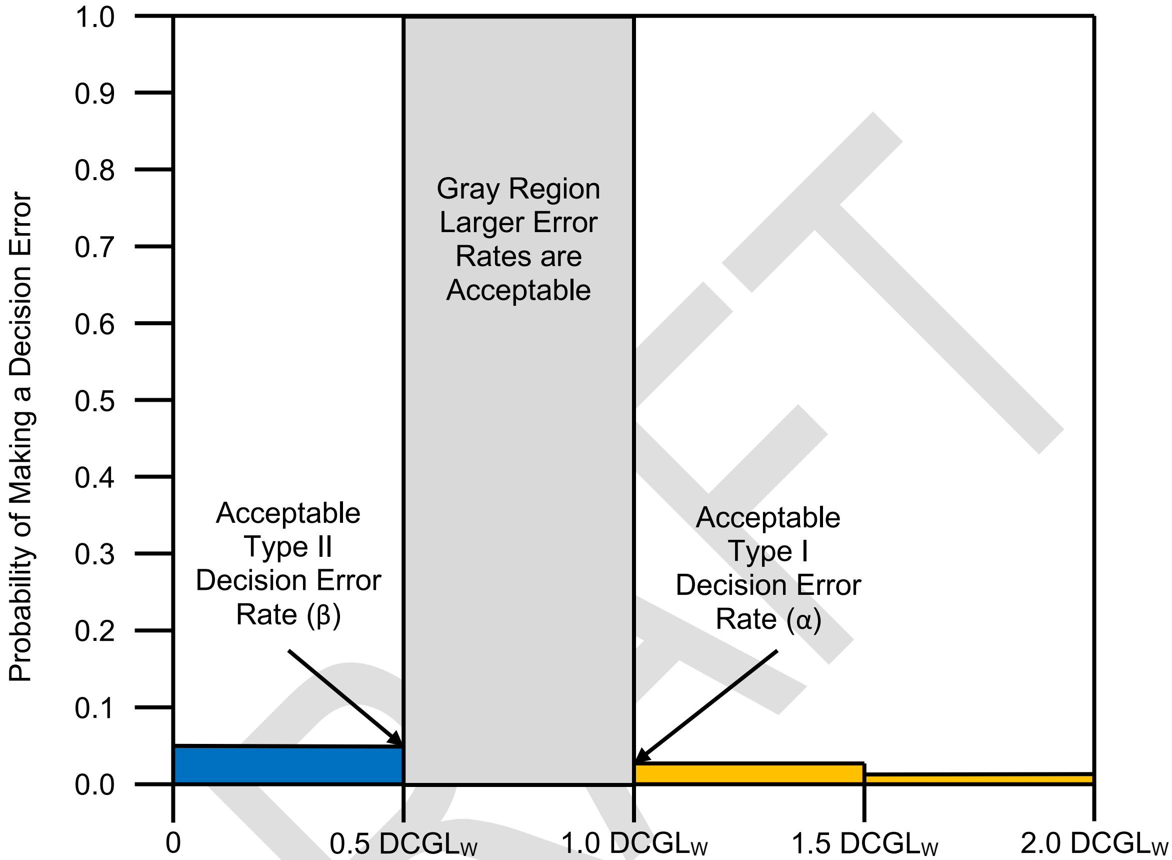


Figure D.9: Example of a Scenario A Error Chart Illustrating the Decision Rule for the Final Status Survey

D.1.7 Develop the Detailed Plan for Obtaining Data

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.

Six activities are included in this step:

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

2. Develop general data collection design alternatives. MARSSIM **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, relaxing other project constraints (e.g., schedule).
   - Change the boundaries—it may be possible to reduce measurement costs 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 of 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.1.7.1 Measurement Quality Objectives

The following discussion of MQOs is adapted from the Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME; NRC 2009) **Section 3.8.** 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. The selection of a measurement method is discussed in more detail in **Chapter 6.** The availability of measurement methods and the amount of resources required to implement specific measurement methods is an important factor in selecting between different survey designs, or in reducing the number of options to be considered when developing potential FSS designs.

A critical element of the measurement method evaluation is to identify project MQOs. Examples of MQOs are described in the following sections. The identification of measurement methods is directly or indirectly related to—

- identification of radionuclides of concern
- location of residual radioactive material
- application of action levels
- 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 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 minimum detectable concentration, or 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 lists of 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 if they are capable of meeting the objectives for measurability.

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 action level. 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 below).

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 (NRC 2004) provides examples on developing MQOs for measurement method uncertainty of laboratory measurement techniques.

Detection Capability

The MDC is recommended as the MQO for defining the detection capability and is an appropriate MQO when decisions are to be made based on a single measurement as to whether residual radioactive material is present or not. **Section 6.3** provides guidance on calculation of the appropriate actual MDC. Additional information on calculating the MDC can be found in MARLAP (Chapter 19, Appendix C; NRC 2004).

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.

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 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 action level 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, where 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 (^{226}Ra) and ^{235}U 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 ^{226}Ra decay products or chemical separation prior to measurement can be used to accurately quantify the radionuclides.

Documented measurement methods should include information on specificity. MARSSIM **Table 7.2** lists examples of references providing laboratory measurement methods. NUREG-1505 (NRC 1998) 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.

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 if 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. A limited list of examples of consensus standards is below:

- ANSI N42.12-1994, American National Standard Calibration and Usage of Thallium-Activated Sodium Iodide Detector Systems for Assay of Radionuclides
- ANSI N42.17A-2003, American National Standard Performance Specifications for Health Physics Instrumentation—Portable Instrumentation for Use in Normal Environmental Conditions
- ANSI N42.17C-1989, American National Standard Performance Specifications for Health Physics Instrumentation—Portable Instrumentation for Use in Extreme Environmental Conditions
- ANSI N42.34-2015, American National Standard Performance Criteria for Handheld Instruments for the Detection and Identification of Radionuclides
- IEEE 309-1999/ANSI N42.3-1999, Institute of Electrical and Electronics Engineers, Inc. Standard Test Procedures and Bases for Geiger Mueller Counters
- ASTM E1169-2002, Standard Guide for Conducting Ruggedness Tests

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 1994). 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 Uniform Federal Policy for Implementing Environmental Quality Systems (UFP-QS) was developed to facilitate consistent implementation of the quality system requirements in Section 5 (Part A) of American National Standards Institute/American Society for Quality (ANSI/ASQ) E4, "Quality Systems for Environmental Data and Technology Programs—Requirements with Guidance for Use" (ANSI/ASQ 2004). Similarly, the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP) (EPA, 2005b) has been 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 Requirements for Quality Assurance Project Plans (EPA 2001b), 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. This scoping process is covered in detail in **Section D.1.**

Among the scoping topics of consideration for MARSSIM are—

- 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** addresses 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 are presented in **Section D.1.9. 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.

[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.

D.2.3 Measurement and Data Acquisition

The Measurement and Data Acquisition section of the QAPP 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 prior to 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 quality control 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

These are the last element groups in the UFP-QAPP. The assessment/oversight element group ensures 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 resultant data quality is adequate for its 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 data set 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 designed to specifically 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.10** illustrates where data verification, data validation, and DQA fit into the assessment phase. **Section D.4** provides detailed guidance on data verification and validation.

There are five steps in the DQA process:

1. Review the DQOs 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 data set 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 and 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 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. Further information on instrument calibration and data conversion is given in **Sections 6.6.4 and 6.7.**

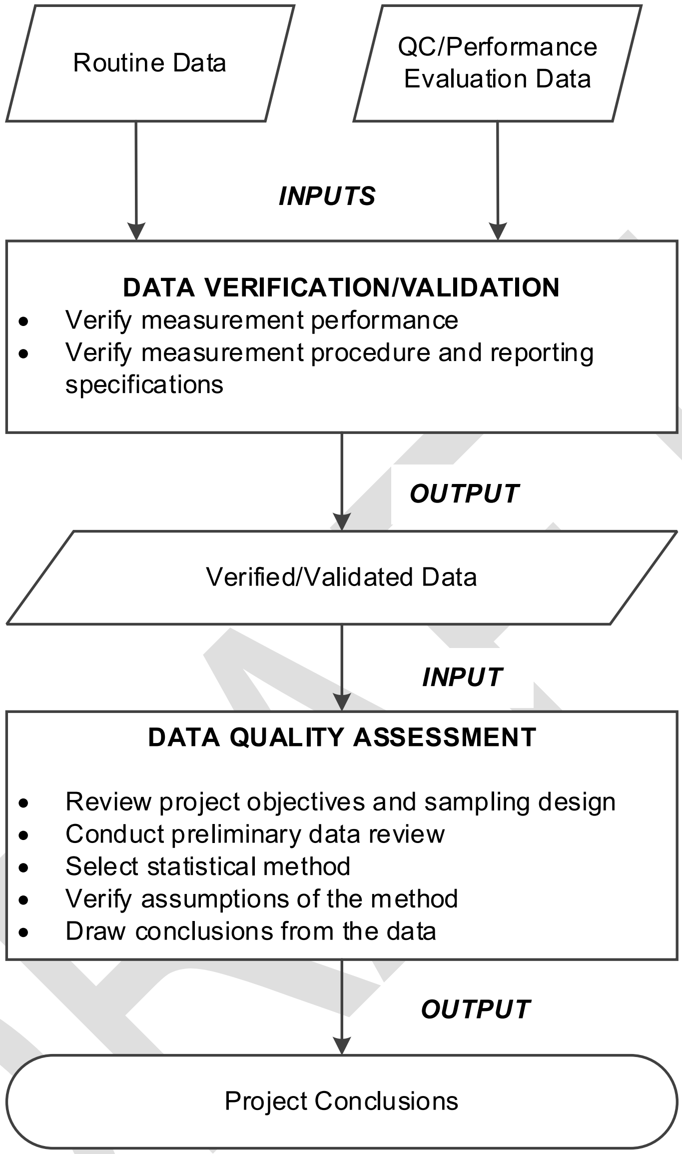


Figure D.10: The Assessment Phase

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

- mean
- standard deviation
- median

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, the 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), the 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 criterion.

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. As discussed in the previous section, 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 (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. Methods for assessing the power are discussed in **Appendix M.** For example, in Scenario A, if the hypothesis that the survey unit residual radioactive material exceeds the release criteria is accepted, 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 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 too many samples
- overestimating MDCs

If one is unable to show that the DQOs were met with reasonable assurance, a re-survey may be needed. **Table 8.2** summarizes 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 criterion, the result is often obvious without performing the formal statistical analysis. **Tables 8.3 and 8.4** describe examples of circumstances leading to specific conclusions based on a simple examination of the data when sampling or direct measurement options are selected.

For scan-only surveys, in Scenario A, an upper confidence limit calculated from the scan data is compared to the $DCGL_W$. In Scenario B, a lower confidence limit calculated is compared to the AL. **Table 8.5** describes 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

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

reclassification is not necessary. The investigation level appropriate for each class of survey unit and type of measurement is shown in **Section 5.3.8, Table 5.4.**

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 on 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.

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 survey QAPP, inspections, surveillances, and audits are conducted throughout to evaluate that the survey process as conducted continues to adhere to established SOPs and plans and that survey and laboratory instruments and measurement systems are producing reliable results. 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 and report deficiencies or problems that they encounter 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 of time (e.g., weeks instead of days) and for equipment that is owned by a company and frequently used to collect survey data. Surveys that are accomplished in one or two 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 more likely to benefit from a detailed technical review 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 and laboratory survey instruments and measurement systems can include check standards for use to test field instruments or measurement systems or performance evaluation samples that are sent to radioanalytical laboratories. As stated above, establishing control charts to check standard results on long-term projects is useful in evaluating field survey instrumentation 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 the performance of survey instruments or measurement systems. Performance evaluation samples sent to laboratories should be of a matrix that is as similar to the actual sampling media as possible 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 may improve data quality, reduce uncertainty, and eliminate the need to qualify or reject data.

Data validation is often defined by six data descriptors:

1. reports to decision makers (**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 if 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.

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

D.4.2.1 Reports to Decision Maker

Data and documentation supplied to the decision maker should be evaluated for completeness and appropriateness and to determine if any changes were made to the survey plan during the course of work. The survey plan discusses the surveying, sampling, and analytical design and contains 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 a variety of data descriptors.

D.4.2.2 Documentation

Field and laboratory documentation are utilized 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:

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 Action
Reports to Decisionmaker	• Site description • Survey design with measurement locations • Measurement method uncertainties and detection capabilities • Background radiation data • Results on 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 • Re-surveying or re-sampling • Correct deficiencies
Data Sources	• Historical data used meets DQOs	• Potential for Type I and Type II decision errors • Lower confidence of data quality	• Resurveying, resampling, or reanalysis for unsuitable or questionable measurements

Data Descriptor	Suggested Content or Consideration	Impact if Not Met	Corrective Action
Measurement Method Uncertainty and Detection Capability	• Routine methods used to quantify radionuclides of potential concern	• Potential for Type I and Type II decision errors	• Resurveying, resampling, or reanalysis • Documented statements of limitation
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
Data Quality Indicators	• 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	• Resurveying or resampling • Perform qualitative site investigation • Documented discussion of potential limitations

Abbreviations: DQOs = Data Quality Objectives; RSSI = Radiation Survey and Site Investigation; SOPs = standard operating procedures; QC = quality control.

- *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 (see **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 in cases in which 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 (NRC 2004).

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, calculating measurement uncertainties, etc. 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 data quality indicators 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 are addressed during the HSA and are discussed in **Section 3.4.1.**

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, report the actual result of the analysis. Do 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 quantitation may be low. Therefore, MARSSIM recommends that the MDC should be less than 50 percent of the DCGL. Information concerning non-detects 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 includes the counting uncertainty of the measurement instrumentation and the sum of the errors associated with the measurement system. The counting uncertainty is essentially a function of the square root of the number of net counts captured by measurement 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 vs. 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 (NRC 2004) 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 varies. The level and depth of the data review may be determined during the planning process and 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

A different level or depth of data review may be indicated by the results of this evaluation. 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 in the contract laboratory program: a normal, not detected (less than critical value) result (U) or <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 (see **Section 2.3.1**).

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.

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** presents a summary of the QC measurements and the data use implications.

<u>Precision</u>

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 error 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 error 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 error 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

Table D.4: Use of Quality Control Data

Quality Control Criterion	Effect on Identification When Criterion Is Not Met	Quantitative Bias	Use
Spikes (Higher-Than-Expected Result)	Potential exists for incorrectly deciding a survey unit does not meet the release criterion.	High	Use data as upper limit.
Spikes (Lower-Than-Expected Result)	Potential exists for incorrectly deciding a survey unit does meet the release criterion.[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 criterion.	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.

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 (NRC 2004) 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-5, EPA Guidance Environmental Data Verification and Validation (EPA 2002a).

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 Action
• Confidence level 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.

<u>Bias</u>

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 process, 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, there are a limited number of options available for performing bias assessment measurements. Perhaps the best estimate of bias for scanning and direct measurements is to collect samples from locations where scans or direct measurements were performed, analyze the samples in a laboratory, and compare 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.

There are several types of bias assessment samples 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.

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.

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 Action
• Matrix spikes to assess bias of non-detects 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: If blank 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 $DCGL_W$, assess sources of potential contamination to prevent recurrence of conditions leading to contamination.

Abbreviations: QC = quality control; $DCGL_W$ = wide-area derived concentration guideline level.

Accuracy is determined by analyzing a reference material of known radionuclide concentration or by re-analyzing 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.11**).

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

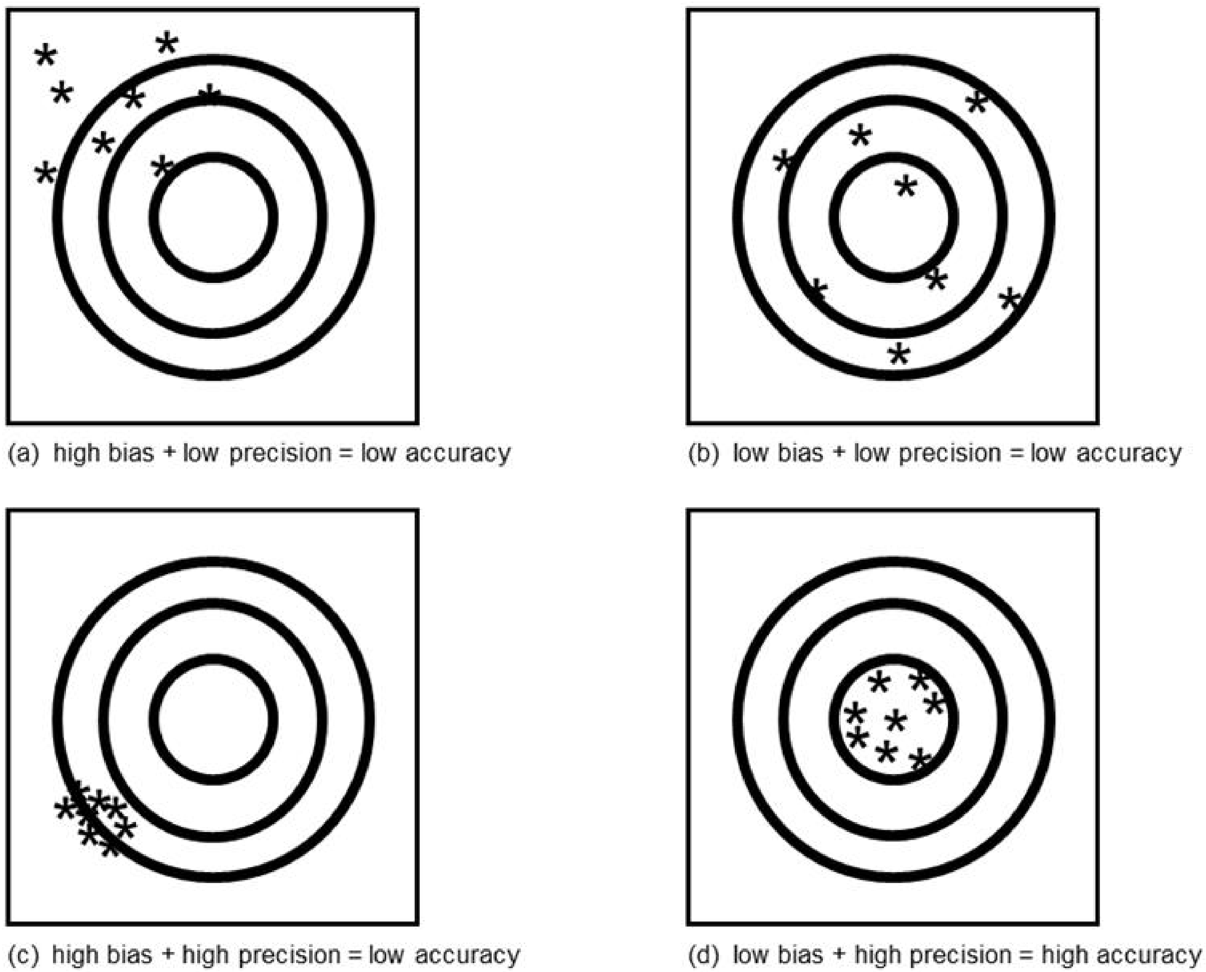


Figure D.11: Graphical Representation of Accuracy

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 of 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.

<u>Representativeness and Detection Capability</u>

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—

- 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, a sufficient number of 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 indicates that a survey unit is just below the established release criteria but the data is 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 Action
• 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 site (fixed vs. non-fixed). • Analytical data are documented as specified in the survey design. • MDCs are sufficiently below release criteria.	• Bias is high or low in estimate of extent and quantity of residual radioactive material. • Potential exists for incorrectly deciding a survey unit does meet the release criterion. • 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 are 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 reanalyses 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.

Abbreviation: MDC = minimum detectable concentration.

Comparability

Comparability is the qualitative term that expresses the confidence that two data sets can contribute to a common analysis and interpolation. Comparability should be carefully evaluated to establish whether two data sets 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 are 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 data sets from different analyses for the same radionuclides. The assessment of data quality indicators determines if analytical results being reported are equivalent to data obtained from similar analyses. Only comparable data sets 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 data sets.

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

- Two data sets 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 data sets.
- The time of measurements of certain characteristics (variables) should be similar for both data sets.
- Measuring devices used for both data sets should have similar detection capabilities.
- Rules for excluding certain types of observations from both samples should be similar.
- Samples within data sets 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 data sets should be of the same order of magnitude.

These characteristics vary in importance depending on the final use of the data. The closer two data sets 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 Action
• 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 factored into the results.	• Non-additivity 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.

<u>Completeness</u>

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 should be considered to be all data that were found to be usable through the data verification and validation process.

Completeness for measurements is calculated by **Equation (**D-1)**:**

$$\% \text{ Completeness} = \frac{(\text{Number of Valid Measurements}) \times 100}{\text{Total Number of Measurements Planned}} \qquad \text{(D-1)}$$

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 actually 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.

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

D.4.2.7 Selection and Classification of Survey Units

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 the classification used to plan the survey is supported by the results of 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

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 Action
• 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 criterion. • 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.

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.

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.

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.

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 initially set to equal one-half of the $DCGL_W$. This becomes important because the Type II decision error rate is calculated at the LBGR.

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 that a retrospective power analysis at the $DCGL_W$ be completed 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.

E RANKED SET SAMPLING

E.1 Introduction

This appendix provides an approach for augmenting Final Status Surveys (FSSs) involving hard-to-detect (HTD) radionuclides in soil with ranked set sampling (RSS) strategies. HTD radionuclides are typically those that emit alpha or beta particles, but no gamma rays, making them hard to detect and quantify with scan measurements, especially in soil. Whereas laboratory analysis of soil samples can provide concentrations at the sample locations, for comparison with an average Derived Concentration Guideline Level ($DCGL_W$), scanning to perform the elevated measurement comparison (EMC) is often impractical.

RSS relies on a two-phase sampling procedure. Phase 1 uses professional judgment combined with a relatively inexpensive field screening method to rank a parameter of interest (e.g., field survey detector count rates roughly corresponding to radionuclide concentrations in soil) within N field screening measurement locations. The ranking of subsets within N field screening locations then forms the basis in Phase 2 for selecting a much smaller number of n locations to collect soil samples to be submitted for laboratory analysis. The screening method selected must have a relative correlation to the concentration of the radionuclide in soil for this procedure to be effective. For example, the initial screening method can be used to rank the probable concentrations as low, medium, or high for a given subset of investigation locations.

The RSS approach can provide a method for increasing the probability of detecting areas of HTD residual radioactive material within Class 1 survey units that may go undetected by the analysis of only the smaller number of samples and the associated sample spacing required by simple random sampling (SRS). If the grid spacing of the field screening measurements is sufficiently small, the probability of missing an area of elevated concentration of radioactive material can be reduced below a value agreed on as part of the process of establishing data quality objectives (DQOs).

One advantage to RSS is that it can provide a more statistically powerful test with the same number of laboratory samples as the SRS method described in **Chapter 5** and corresponding reductions in the probability of Type I and Type II errors.

This approach is intended for alpha- or beta-emitters in soil (referred to as HTDs when in soil) when there is no gamma radiation component associated with the radionuclide(s) of concern and/or there is no surrogate relationship that can be established to form the basis for a scan Minimum Detectable Concentration (MDC).

The RSS approach described in this appendix is only one of several possible methods for designing HTD radionuclide surveys. As an example, some compositing techniques may provide some additional capability for increasing sample density for HTD radionuclides where scanning is not possible. When using compositing as a method for looking for areas of elevated radioactive material, special attention needs to be given to measurement quality objectives (MQOs) including detection capability and measurement quantification. Vitkus (2012) provides more information on this alternative method.

Performing an RSS survey requires a much greater level of expertise in survey planning and implementation than a traditional Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) survey requires. For that reason, the planning team may wish to consult with additional experts in the fields of survey design, instrumentation, and statistics before developing an RSS survey.

E.1.1 Ranked Set Sampling Considerations and Limitations

Before utilizing RSS, the user should[1] determine under what conditions RSS becomes a cost-effective sampling method where even the field screening measurements have a cost. In other words, when does RSS become appropriate and cost favorable for field screening and sampling versus the collection and analysis of additional samples described in **Chapter 5**. Pacific Northwest National Laboratory's Visual Sample Plan software includes an RSS module and associated cost component to assist the user in the development of an RSS plan.

Using the RSS method when the ranking is imperfect can result in the rejection of the null hypothesis when there is insufficient evidence to do so. In the case where there is no correlation between the ranking and quantity of interest, the selection is random, and the SRS hypothesis is more appropriate. However, using the SRS sign test for results generated using the RSS method results in a less powerful test; the probability rejecting the null hypothesis is higher than it would be using the RSS sign test.

Therefore, the user should:

- Evaluate cost ratios comparing RSS to SRS.
- Evaluate cost ratios for data sets consisting of professional judgment measurements and analyzed samples.

E.1.2 Advantages of Ranked Set Sampling

The RSS approach is adaptable for field use and has several advantages (especially for heterogeneous population distributions that are expensive to sample):

- Provides a more precise estimate of the mean sample concentration (decreased statistical uncertainty);
- Although not necessarily an advantage in this specialized application of RSS, under normal use scenarios, the process requires collection of fewer samples (and concomitant reduction in the number of analyses and therefore analytical costs);
- Increases the probability of collecting representative samples;
- Increases likelihood of detecting areas of elevated concentration of radioactive material; and
- Improves performance for statistical procedures (e.g., testing for compliance).

E.1.3 Requirements

The RSS approach described here fundamentally requires a field screening method with sufficient detection capability to enable the user to rank likely relative concentrations into a minimum of two ranking categories (low and high) to a recommended maximum of five ranked

[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.

set size categories (low, medium-low, medium, medium-high, and high). The nominal number of ranking categories used in the examples in this appendix is three (low, medium, and high).

To rank the samples, a field screening technique is required that provides information about which sample is the highest in terms of the concentration of radioactive material, second highest, and so forth to the lowest. The field screening method will typically involve some type of field measurement of the samples in a consistent counting geometry. For example, the field measurement might measure the response (count rate) of an appropriate survey instrument to a fixed amount of sample material. As the interest is only in the relative comparison of the field measurements, the field screening technique does not necessarily need to be calibrated to estimate the actual concentration of radioactive material. However, any field instruments used should still be operationally checked to ensure that they are operating properly and meet the applicable MQOs. Additionally, efforts should be made to eliminate or minimize any uncertainty in making these relative measurements. For example, using the same instrument to rank a set of samples eliminates the possibility of mis-ranking the samples as a result of calibration differences between instruments.

If m is the number of ranking categories, the procedure is first to select m sample locations, and rank the locations in terms of concentration from lowest to highest. From this first set of m sample locations, a sample is collected at the location with the lowest expected concentration, usually the location of the lowest field measurement. The procedure is then repeated by selecting other m locations but taking the sample this time from the location with the second lowest expected concentration. The process is repeated until a total of m samples have been collected. For $m = 3$, the set of samples include the sample with lowest expected concentration from the first set of three locations, the sample with second lowest expected concentration from the second set of three locations, and the sample with highest expected concentration from the third set of three locations. In the likely case where more than m samples are required, this procedure is repeated r times until enough samples have been collected. Each set of m samples is referred to as a cycle and r is the number of cycles.

E.1.4 Key Parameters

Since each of the r cycles results in the collection and analysis of m laboratory samples, the total number of laboratory samples to be collected and analyzed, n, is:

$$n = r \times m \quad \text{(E-1)}$$

Additionally, since for each of the r cycles, m sample locations are selected from a larger population of m^2 field screening measurement locations. The total number of field screening measurements, N, is:

$$N = r \times m^2 \quad \text{(E-2)}$$

The total number of field screening measurements, N, is therefore m times as large as the number of samples collected for laboratory analysis:

$$N = n \times m \quad \text{(E-3)}$$

Example 1 illustrates how locations for the collection of soil samples for laboratory analysis can be selected from a larger population of locations, based on field measurements.

E.1.5 Use of Ranked Set Sampling in MARSSIM

Use of RSS is similar to the SRS described in MARSSIM, with a number of steps in the process replaced with steps modified to account for the differences between RSS and SRS. These steps include the following:

- Calculation of the required number of field screening measurement locations and the corresponding number of laboratory samples (replaces **Section 5.3.4**)
- Modification of the number of field screening measurement locations for the EMC (replaces **Section 5.3.5**)
- Application of the statistical test, including the calculation of the critical value (replaces **Section 8.3.2**)

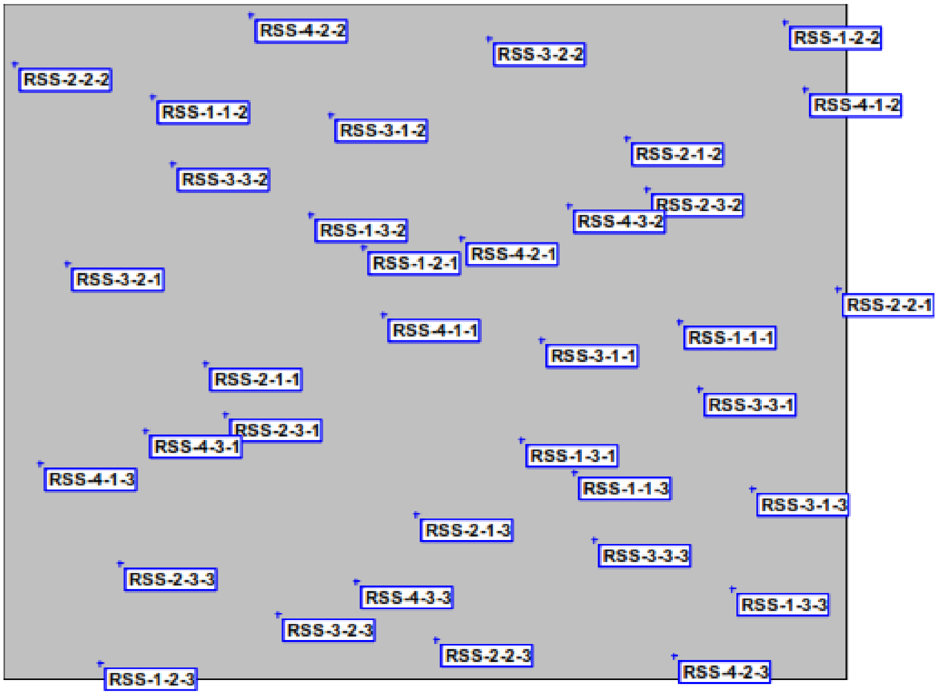
Other aspects of MARSSIM unaffected by the differences between RSS and SRS should be performed in accordance with the information in MARSSIM. These include, but are not limited to the following:

- The establishment of DQOs and MQOs
- Selection of measurement methods
- Exploratory data analysis
- Quality assurance/quality control

Section E.2 describes in more detail the integration of RSS into MARSSIM.

Example 1: Integration of Ranked Set Sampling into a MARSSIM Final Status Survey

Twelve samples were to be collected from 36 randomly selected locations where field measurements of the radiation level were made. The 36 field measurements were divided into four ranking cycles ($r = 4$) with three sets of three field measurements each ($m = 3$). Field locations, as shown below, were numbered using the following convention: cycle-set-location.



Note that for $r = 4$ and $m = 3$,

$$N = r \times m^2 = 4 \times 3^2 = 36$$
$$n = r \times m = 4 \times 3 = 12$$

The table below shows the results of the 36 field measurements. Laboratory samples were collected at the following twelve locations (shaded in the table) for analysis: 1-1-2, 1-2-2, 1-3-3, 2-1-3, 2-2-1, 2-3-1, 3-1-2, 3-2-2, 3-3-1, 4-1-3, 4-2-1, and 4-3-3.

No.	Count Rate (cpm)	Rank	No.	Count Rate (cpm)	Rank	No.	Count Rate (cpm)	Rank	No.	Count Rate (cpm)	Rank
1-1-1	6,129	2	2-1-1	6,305	2	3-1-1	6,373	3	4-1-1	5,836	3
1-1-2	5,389	1	2-1-2	6,491	3	3-1-2	5,701	1	4-1-2	5,691	2
1-1-3	6,150	3	2-1-3	6,181	1	3-1-3	6,221	2	4-1-2	5,325	1
1-2-1	5,243	1	2-2-1	6,281	2	3-2-1	5,627	1	4-2-1	5,962	2
1-2-2	5,567	2	2-2-2	6,423	3	3-2-2	5,761	2	4-2-2	5,345	1
1-2-3	5,785	3	2-2-3	6,233	1	3-2-3	5,781	3	4-2-3	6,007	3
1-3-1	5,577	1	2-3-1	5,930	3	3-3-1	6,672	3	4-3-1	5,425	2
1-3-2	6,209	2	2-3-2	5,378	1	3-3-2	5,504	1	4-3-2	5,299	1
1-3-3	6,416	3	2-3-3	5,384	2	3-3-3	6,245	2	4-3-3	7,259	3

Abbreviation: cpm = counts per minute.

The 12 samples collected were analyzed. The results are provided below.

Sample No.	Location ID	Data (Bq/kg)
1	1-1-2	32.0
2	1-2-2	33.2
3	1-3-3	38.74
4	2-1-3	36.8
5	2-2-1	37.2
6	2-3-1	35.2
7	3-1-2	34.0
8	3-2-2	34.4
9	3-3-1	39.6
10	4-1-3	31.6
11	4-2-1	35.6
12	4-3-3	43.2

Abbreviation: Bq/kg = becquerels per kilogram.

E.2 Integration of Ranked Set Sampling into MARSSIM

E.2.1 Choosing the Statistical Test

The null hypothesis tested using RSS is the same as that for SRS. Under Scenario A, the null hypothesis (H_0) is that median, used as an estimate of the mean, of the underlying distribution is greater than or equal to the $\mathrm{DCGL_W}$, while the alternative hypothesis (H_1) is that medianof the underlying distribution is less than the $\mathrm{DCGL_W}$.

$$H_0 : \text{median} \geq \mathrm{DCGL_W},$$

$$H_1 : \text{median} < \mathrm{DCGL_W}$$

Under Scenario B, the null hypothesis (H_0) is that the median, used as an estimate of the mean, of the underlying distribution is less than or equal to the $\mathrm{DCGL_W}$, while the alternative hypothesis (H_1) is that the median of the underlying distribution is greater than the $\mathrm{DCGL_W}$.

$$H_0 : \text{median} \leq \mathrm{DCGL_W},$$

$$H_1 : \text{median} > \mathrm{DCGL_W}$$

There are RSS versions of the two nonparametric statistical tests described in MARSSIM. When the contribution of the radionuclide to background cannot be neglected and/or the results are not radionuclide-specific, MARSSIM recommends the Wilcoxon Rank Sum (WRS) test. The Mann-Whitney-Wilcoxon Test is equivalent to the WRS test, and there is an RSS version of the Mann-Whitney-Wilcoxon Test. Although the use of the RSS version of the Mann-Whitney-Wilcoxon Test is not described in this appendix, more information about the RSS Mann-Whitney-Wilcoxon Test can be found in *Ranked Set Sampling: Theory and Applications* (Chen et al., 2004) and other references on statistics.

The sign test is an appropriate test for both the RSS and SRS application when the contribution of the radionuclide to background can be neglected and the results are radionuclide-specific. For radionuclides that are not in the background, or in the background at concentrations that are a small fraction of the $\mathrm{DCGL_W}$, the RSS sign test can be used.

The SRS versions of both tests can be used with samples selected using the RSS approach described in **Section E.1.3**; however, the power of the statistical test will likely be reduced, and the probability of Type II errors, failing to reject the null hypothesis when it is false, will be higher. The RSS sign test and its application are described in detail in the remainder of this section.

E.2.2 Calculating the Required Number of Field Screening Measurements for the Ranked Set Sampling Sign Test

The required number of field screening measurements for the RSS sign test depends on the same survey design parameters as the SRS sign test:

- The standard deviation of the underlying distribution (σ)
- The width of the gray region (Δ)
- The Type I decision error limit (α)
- The Type II decision error limit (β)

The required number of field screening measurements for the RSS sign test can be determined by calculating the statistical power of the RSS sign test for the parameters described above for different numbers of field screening measurements. The results of these calculations are given in **Tables E.1 to E.3**. Similar to the values given in **Table 5.5**, these values have been increased by 20 percent to account for missing or unusable data and then rounded up to the nearest multiple of 5, 4, or 3, respectively.

Example 2 provides an illustration on determining the number of required laboratory samples and field screening measurements.

Example 2: Example of Determination of the Number of Required Laboratory Samples and Field Screening Measurements

An FSS was designed. The Type I error was specified as 0.05, while the Type II error, defined at $\Delta/\sigma = 2.0$, was specified as 0.10. The planning team decided to use three ($m = 3$) categories to rank the samples as low, medium, and high. Using **Table E.3**, reproduced in part below, the number of required laboratory samples is 12.

α	β	Δ/σ											
		0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.4**	**1.6**	**1.8**	**2.0**	**2.5**
0.05	**0.01**	> 54	> 54	51	42	30	27	24	15	12	12	12	12
	0.025	> 54	51	42	30	27	27	15	12	12	12	12	12
	0.05	> 54	48	42	27	27	18	15	12	12	12	12	9
	0.1	51	42	27	27	18	15	12	12	12	12	12	9
	0.25	42	27	24	15	12	12	12	12	12	9	9	9

Abbreviations: α = Type I decision error limit ; β = Type II decision error limit; Δ/σ = standard deviation of the underlying distribution divided by the width of the gray region.

The 12 laboratory samples required 36 field screening measurements.

Table E.1. Required Number of Laboratory Samples for Ranked Set Sampling Sign Test for 5 Sets Per Cycle

α	β	Δ/σ											
		0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.4**	**1.6**	**1.8**	**2.0**	**2.5**
0.01	**0.01**	>90	75	50	40	40	30	25	20	15	15	15	15
	0.025	80	60	45	40	40	30	25	15	15	15	15	15
	0.05	75	50	40	40	30	25	20	15	15	15	15	15
	0.1	60	45	40	30	25	25	15	15	15	15	15	15
	0.25	40	40	30	25	15	15	15	15	15	15	15	15
0.025	**0.01**	80	55	50	40	30	25	20	20	15	15	15	15
	0.025	75	50	45	30	25	25	20	15	15	15	15	15
	0.05	60	50	40	30	25	20	20	15	15	15	15	15
	0.1	50	45	30	25	20	20	15	15	15	15	15	15
	0.25	40	25	20	20	15	15	15	15	15	15	15	15
0.05	**0.01**	75	55	40	30	30	25	20	20	15	15	15	15
	0.025	55	45	30	30	25	25	20	15	15	15	15	15
	0.05	55	40	30	30	25	20	20	15	15	15	15	15
	0.1	45	30	30	25	20	20	15	15	15	15	15	15
	0.25	30	25	20	20	15	15	15	15	15	15	15	15
0.1	**0.01**	55	40	40	30	25	20	15	15	15	15	15	15
	0.025	50	40	30	25	20	15	15	15	15	15	15	15
	0.05	40	40	25	20	15	15	15	15	15	15	15	15
	0.1	40	25	20	15	15	15	15	15	15	15	15	15
	0.25	20	15	15	15	15	15	15	15	15	15	15	15
0.25	**0.01**	45	40	25	20	20	20	15	15	15	15	15	15
	0.025	40	25	20	20	20	15	15	15	15	15	15	15
	0.05	30	20	20	20	15	15	15	15	15	15	15	15
	0.1	20	20	20	15	15	15	15	15	15	15	15	15
	0.25	20	15	15	15	15	15	15	15	15	15	15	15

Abbreviations: α = Type I decision error limit ; β = Type II decision error limit; Δ/σ = standard deviation of the underlying distribution divided by the width of the gray region.

Table E.2. Required Number of Laboratory Samples for Ranked Set Sampling Sign Test for 4 Sets Per Cycle

α	β	Δ/σ											
		0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.4**	**1.6**	**1.8**	**2.0**	**2.5**
0.01	**0.01**	> 72	68	60	44	36	32	24	20	20	16	12	12
	0.025	> 72	64	48	36	32	32	20	20	16	12	12	12
	0.05	> 72	60	44	36	32	24	20	16	16	12	12	12
	0.1	64	48	36	32	24	20	20	16	12	12	12	12
	0.25	48	36	32	20	20	20	12	12	12	12	12	12
0.025	**0.01**	> 72	64	44	40	36	24	24	16	16	16	12	12
	0.025	68	60	44	36	24	24	16	16	16	12	12	12
	0.05	64	44	40	36	24	24	16	16	16	12	12	12
	0.1	60	40	36	24	24	16	16	16	12	12	12	12
	0.25	40	36	24	16	16	16	12	12	12	12	12	12
0.05	**0.01**	> 72	56	40	36	32	20	20	16	16	16	12	12
	0.025	64	48	36	32	20	20	16	16	16	12	12	12
	0.05	56	40	36	32	20	20	16	16	16	12	12	12
	0.1	40	36	32	20	20	16	16	16	12	12	12	12
	0.25	36	20	20	16	16	16	12	12	12	12	12	12
0.1	**0.01**	64	48	36	32	24	20	20	12	12	12	12	12
	0.025	56	36	32	24	20	20	12	12	12	12	12	12
	0.05	48	32	24	24	20	20	12	12	12	12	12	12
	0.1	36	24	24	20	20	12	12	12	12	12	12	12
	0.25	24	20	20	12	12	12	12	12	12	12	12	12
0.25	**0.01**	44	36	24	20	20	16	16	12	12	12	12	12
	0.025	36	32	24	20	16	16	12	12	12	12	12	12
	0.05	32	24	20	16	16	16	12	12	12	12	12	12
	0.1	24	20	16	16	16	12	12	12	12	12	12	12
	0.25	20	16	16	12	12	12	12	12	12	12	12	12

Abbreviations: α = Type I decision error limit ; β = Type II decision error limit; Δ/σ = standard deviation of the underlying distribution divided by the width of the gray region.

Table E.3. Required Number of Laboratory Samples for Ranked Set Sampling Sign Test for 3 Sets Per Cycle

α	β	Δ/σ											
		0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.0	2.5
0.01	0.01	> 54	> 54	> 54	48	45	33	30	24	18	15	15	12
	0.025	> 54	> 54	> 54	45	33	30	27	18	15	15	12	12
	0.05	> 54	> 54	45	42	30	30	24	18	15	12	12	9
	0.1	> 54	> 54	45	30	30	27	18	15	12	12	12	9
	0.25	> 54	42	30	27	24	18	15	12	12	9	9	9
0.025	0.01	> 54	> 54	> 54	48	33	33	24	18	18	15	15	12
	0.025	> 54	> 54	48	33	33	27	18	18	15	15	12	12
	0.05	> 54	48	42	33	27	18	18	18	15	12	12	9
	0.1	> 54	48	33	27	18	18	18	15	12	12	12	9
	0.25	48	33	24	18	18	18	15	12	12	9	9	9
0.05	0.01	> 54	> 54	51	42	30	27	24	15	12	12	12	12
	0.025	> 54	51	42	30	27	27	15	12	12	12	12	12
	0.05	> 54	48	42	27	27	18	15	12	12	12	12	9
	0.1	51	42	27	27	18	15	12	12	12	12	12	9
	0.25	42	27	24	15	12	12	12	12	12	9	9	9
0.1	0.01	> 54	51	42	30	30	18	18	15	12	12	9	9
	0.025	> 54	42	30	30	18	18	15	12	12	9	9	9
	0.05	51	42	30	18	18	18	15	12	9	9	9	9
	0.1	42	30	18	18	18	15	12	9	9	9	9	9
	0.25	30	18	18	15	12	9	9	9	9	9	9	9
0.25	0.01	54	36	30	24	24	18	12	12	12	12	9	9
	0.025	36	30	24	24	18	12	12	12	12	9	9	9
	0.05	30	30	24	18	12	12	12	12	9	9	9	9
	0.1	30	24	15	12	12	12	12	9	9	9	9	9
	0.25	24	12	12	12	12	9	9	9	9	9	9	9

Abbreviations: α = Type I decision error limit ; β = Type II decision error limit; Δ/σ = standard deviation of the underlying distribution divided by the width of the gray region.

Like the SRS sign test, prospective and retrospective power curves can be calculated. The power curve is the probability of rejecting the null hypothesis as a function of the relative difference Δ/σ between the true median concentration and the $DCGL_W$. The power curves for the RSS and SRS sign tests can also be calculated and compared. Chen et al. provide an equation to calculate $1 - \beta_{\text{RSS}}(\Delta)$, the power curve for the RSS sign test[2]:

$$1 - \beta_{\text{RSS}}(\Delta) = \sum_{y=k_{\text{RSS}}+1}^{r\times m} \sum_{(j_1+\cdots+j_r=y)} \prod_{k=1}^{m} \binom{m}{j_k} [p_k]^{j_k} [1 - p_k]^{m-j_k} \quad \textbf{(E-4)}$$

where

$$p_k = 1 - B\big(k, r + 1 - k; H(0)\big) \quad \textbf{(E-5)}$$

where $B(\alpha, \beta; x)$ is the distribution of the beta distribution with parameters α and β, and $H(0) = F(-\Delta)$ is the distribution function under the alternative hypothesis evaluated at $\Delta = 0$ (Chen et al, 2004). For comparison, the power curve for the SRS sign test, $1 - \beta_{\text{SRS}}(\Delta)$ (see **Appendix M**), is calculated using the following equation:

$$1 - \beta_{\text{SRS}}(\Delta) = \sum_{y=k_{\text{SRS}}+1}^{n} \binom{n}{y} [1 - H(0)]^{y} [H(0)]^{n-y} \quad \textbf{(E-6)}$$

where n is the number of samples, and $H(0)$ is defined the same as for the RSS sign test.

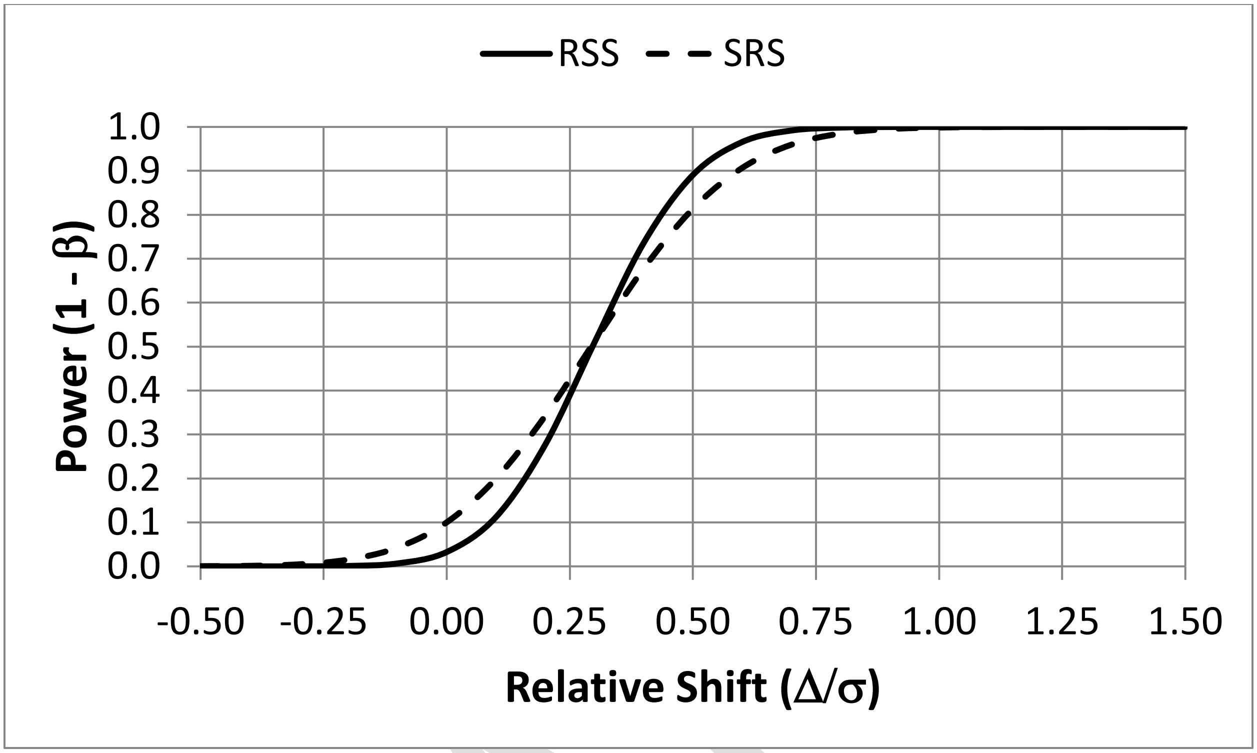
Power curves show how the power changes as a function of the relative shift, Δ/σ. **Figures E.1 and E.2** illustrate RSS and SRS power curves for the same total number of samples and the same critical value. Although the power of both the RSS and SRS Sign tests approach unity for large values of the relative shift, the probability of Type II decision errors will be smaller for the RSS sign test than the SRS test for large enough values of Δ/σ. Likewise, the probability of Type I decision errors is smaller for the RSS Sign test than the SRS Sign test.

E.2.3 Modifying the Number of Field Screening Measurements for the Elevated Measurement Comparison

In addition to the Type I and Type II errors described above, an additional error must also be controlled: the probability (p) of detecting an area of elevated concentration of radioactive material of a given size. The acceptable risk of not detecting an area of elevated concentrations of radioactive material of a given size is defined as $(1 - p)$. The probability of detecting an area of elevated concentration of radioactive material can be estimated using **Table I.5 in Appendix I**.

Before finalizing the survey design, an *a priori* estimate of the size of an area with an elevated concentration of residual radioactive material and the associated $DCGL_{EMC}$ must be determined. Once the size of the area of elevated concentration of radioactive material is determined, the

[2] The equation provided here differs in notation from Chen et al. in notation. Additionally, Chen at al. defined the critical value as the value that the test statistic had to be greater than or equal to (≥) to reject the null hypothesis, instead of the value that the test statistic had to be greater than (>) to reject the null hypothesis.

1. 

2. Figure E.1. Power Curve for 10 Cycles of 3 Sets per Cycle for a Critical Value of 19 ($\alpha = 0.018$) and SRS Power Curve for the Same Critical Value ($\alpha = 0.005$)

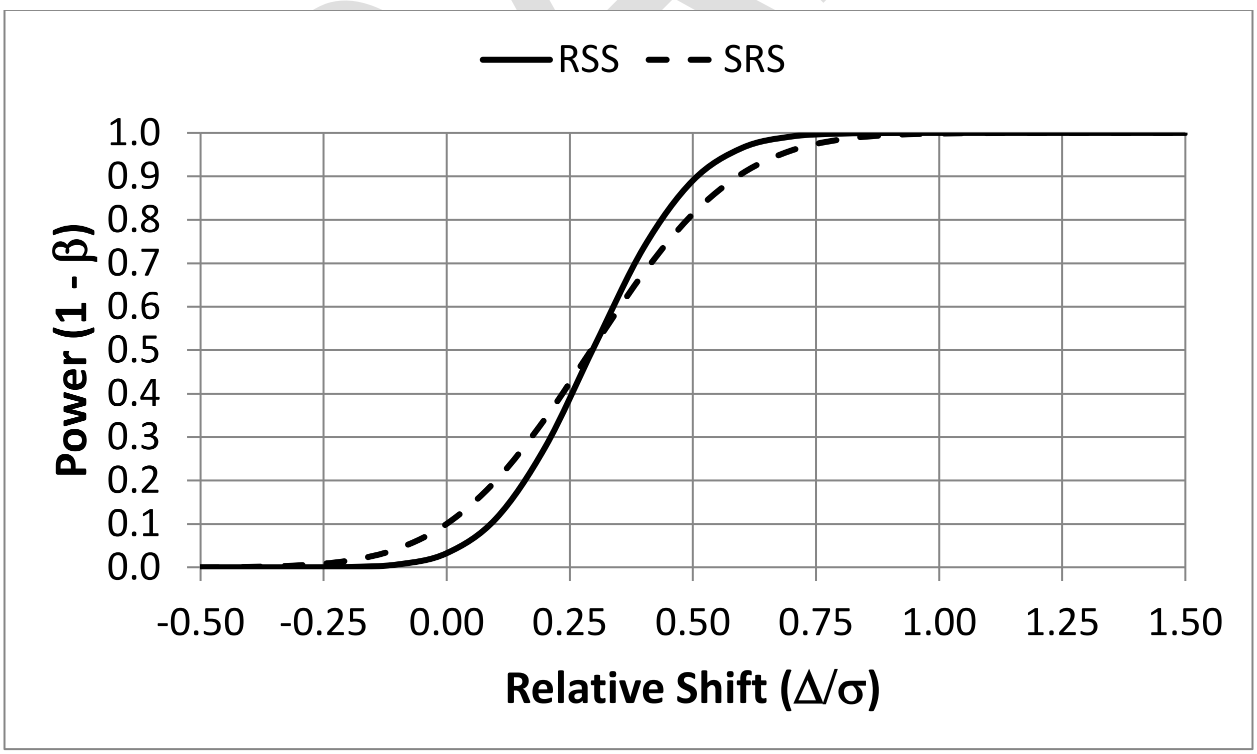
3. 

Figure E.2. Power Curve for 6 Cycles of 5 Sets per Cycle for a Critical Value of 18 ($\alpha = 0.032$) and SRS Power Curve for the Same Critical Value ($\alpha = 0.100$)

RSS approach can be applied to provide a high level of probability that an area of this size will be sampled.

Note that there is a technical issue associated with this *a priori* estimated size. The issue is how to select the size, as stakeholder concerns will likely persist for yet smaller areas with elevated concentrations of residual radioactive material that could again be missed. Therefore, the technical justification may need to consider:

- Inclusion of additional dose modeling details regarding the risks from other small areas of elevated concentrations of residual radioactive material that could go undetected and potentially contribute to the total dose from all remaining source terms across the site and/or,
- A method that uses characterization information to estimate the maximum concentration of residual radioactive material at the site.

The RSS sample mean is an unbiased estimator of the true mean, μ, of the underlying distribution. The RSS sample variance can be calculated using the following equation:

$$s_{\mathrm{RSS}}^2 = \frac{1}{r \times m - 1} \sum_{k=1}^{r} \sum_{i=1}^{m} \left(X_{[k]i} - \bar{X}_{RSS}\right)^2 \qquad \text{(E-7)}$$

The RSS sample variance is not an unbiased estimator of the true variance, σ^2, of the underlying distribution, and the expectation value of the RSS sample variance is greater than or equal to the true variance, σ^2, of the underlying distribution. The use of a conservative estimator of the variance, such as the RSS sample variance, helps ensure that the power of the statistical test will be sufficient. **Example 3** includes the calculation of the RSS sample mean and sample standard deviation for the data in **Example 2**.

Example 3: Example of Calculation of the Ranked Set Sampling Sample Mean and Sample Standard Deviation

The twelve samples collected were analyzed. The results are provided below.

Sample No.	Location ID		Data (Bq/kg)
1	1-1-2	$X_{[1]1}$	32.0
2	1-2-2	$X_{[1]2}$	33.2
3	1-3-3	$X_{[1]3}$	38.4
4	2-1-3	$X_{[2]1}$	36.8
5	2-2-1	$X_{[2]2}$	37.2
6	2-3-1	$X_{[2]3}$	35.2
7	3-1-2	$X_{[3]1}$	34.0
8	3-2-2	$X_{[3]2}$	34.4
9	3-3-1	$X_{[3]3}$	39.6
10	4-1-3	$X_{[4]1}$	31.6
11	4-2-1	$X_{[4]2}$	35.6
12	4-3-3	$X_{[4]3}$	43.2

Abbreviations: Bq/kg = becquerels per kilogram; $X_{[k]i}$ = data for the kth set, ith sample.

For the data from our earlier example, the RSS sample mean is calculated below:

$$\hat{\mu}_{\mathrm{RSS}} = \frac{1}{r \times m} \sum_{k=1}^{r} \sum_{i=1}^{m} X_{[k]i}$$
$$= \frac{1}{4 \times 3} \sum_{k=1}^{4} \sum_{i=1}^{3} X_{[k]i}$$
$$= \frac{1}{12}(32.0 + 33.2 + 38.4 + \cdots + 31.6 + 35.6 + 43.2)\ \mathrm{Bq/kg}$$
$$= 35.93\ \mathrm{Bq/kg}$$

The RSS sample mean is 35.93 becquerels per kilogram (Bq/kg). The RSS sample variance and sample standard deviation are calculated below:

$$s_{\mathrm{RSS}}^2 = \frac{1}{r \times m - 1} \sum_{k=1}^{r} \sum_{i=1}^{m} \left(X_{[k]i} - \bar{X}_{RSS}\right)^2$$
$$= \frac{1}{4 \times 3 - 1} \sum_{k=1}^{4} \sum_{i=1}^{3} \left(X_{[k]i} - \bar{X}_{RSS}\right)^2$$
$$= \frac{1}{11}[(32.0 - 35.93)^2 + \cdots + (43.2 - 35.93)^2]\ \mathrm{Bq^2/kg^2}$$
$$= 11.20\ \mathrm{Bq^2/kg^2}$$

The RSS sample variance is 11.20 $\mathrm{Bq^2/kg^2}$.

$$s_{\mathrm{RSS}} = \sqrt{s_{\mathrm{RSS}}^2}$$
$$= \sqrt{11.20\ \mathrm{Bq^2/kg^2}}$$
$$= 3.35\ \mathrm{Bq/kg}$$

The RSS sample standard deviation is 3.35 Bq/kg.

E.2.4 Application of the RSS Sign Test

For Scenario A, the Sign test is applied as outlined in the following steps:

4. List the survey unit measurements, $X_{[k]i}$, for $k = 1, \ldots, r$ and $i = 1, \ldots, m$
5. Subtract each measurement, $X_{[k]i}$, from the $\mathrm{DCGL_W}$ to obtain the differences: $D_{[k]i} = \mathrm{DCGL_W} - X_{[k]i}$ for $k = 1, \ldots, r$ and $i = 1, \ldots, m$
6. Count the number of positive differences. The result is the test statistic S_{RSS}^{+}. (Note that a positive difference corresponds to a measurement below the $\mathrm{DCGL_W}$ and contributes evidence that the survey unit meets the release criterion.)
7. Large values of S_{RSS}^{+} indicate that the null hypothesis is false. Compare the value of S_{RSS}^{+} to the critical values in **Table E.4**. If S_{RSS}^{+} is greater than the critical value, k_{RSS}, in that table, the null hypothesis is rejected.

For Scenario B, the Sign test is applied as outlined in the following five steps:

1. List the survey unit measurements, $X_{[k]i}$, for $k = 1, \dots, r$ and $i = 1, \dots, m$

2. Subtract the $\mathrm{DCGL_W}$ from each measurement, $X_{[k]i}$, to obtain the differences: $D_{[k]i} = X_{[k]i} - \mathrm{DCGL_W}$, for $k = 1, \dots, r$ and $i = 1, \dots, m$

3. Count the number of positive differences. The result is the test statistic S^{+}_{RSS}. (Note that a positive difference corresponds to a measurement above the $\mathrm{DCGL_W}$ and contributes evidence that the survey unit does not meet the release criterion.)

4. Large values of S^{+}_{RSS} indicate that the null hypothesis is false. Compare the value of S^{+}_{RSS} to the critical values in **Table E.4**. If S^{+}_{RSS} is greater than the critical value, k_{RSS}, in that table, the null hypothesis is rejected.

The power in the RSS method is dependent on the ability to rank the samples in terms of the quantity of interest. The methods presented here are only valid when the ranking is perfect.

For this reason, the following is recommended when there is concern about the ranking mechanism:

- If the test statistic is greater than the SRS critical value, reject the null hypothesis.
- If the test statistic is greater than the RSS critical value but less than or equal to the SRS critical value, assess the correlation between the field measurements and laboratory sample results before rejecting the null hypothesis.
- If the test is less than or equal the RSS test statistic, fail to reject the null hypothesis.

Table E.5 provides critical values for the SRS Sign test for various Type I decision error limits to facilitate side-by-side comparison.

Table E.4. Critical Values for the Ranked Set Sampling Sign Test

		α									
		0.001	**0.005**	**0.01**	**0.025**	**0.05**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
$r = 9$	$m = 5$	30	29	28	27	26	25	24	24	23	22
	$m = 4$	25	24	23	22	22	21	20	19	19	18
	$m = 3$	20	19	18	17	17	16	15	15	14	14
	$m = 2$	15	14	13	13	12	11	11	10	9	9
$r = 8$	$m = 5$	27	26	25	24	24	23	22	21	21	20
	$m = 4$	22	21	21	20	19	19	18	17	17	16
	$m = 3$	18	17	16	16	15	14	14	13	12	12
	$m = 2$	13	12	12	11	11	10	9	9	8	8
$r = 7$	$m = 5$	24	23	22	22	21	20	19	19	18	17
	$m = 4$	20	19	18	18	17	16	16	15	14	14
	$m = 3$	16	15	15	14	13	13	12	11	11	11
	$m = 2$	12	11	11	10	10	9	8	8	7	7
$r = 6$	$m = 5$	21	20	19	19	18	17	17	16	15	15
	$m = 4$	17	17	16	16	15	14	14	13	12	12
	$m = 3$	14	13	13	12	12	11	10	10	9	9
	$m = 2$	10	10	9	9	8	8	y	7	6	6
$r = 5$	$m = 5$	18	17	17	16	15	15	14	13	13	12
	$m = 4$	15	14	14	13	13	12	11	11	10	10
	$m = 3$	12	11	11	10	10	9	9	8	8	7
	$m = 2$	8	8	7	7	7	6	6	6	5	5
$r = 4$	$m = 5$	15	14	14	13	13	12	11	11	10	10
	$m = 4$	12	12	11	11	10	10	9	9	8	8
	$m = 3$	10	9	9	8	8	8	7	7	6	6
	$m = 2$	n/a	n/a	6	6	6	5	5	5	4	4
$r = 3$	$m = 5$	12	11	11	10	10	9	9	8	8	7
	$m = 4$	10	9	9	9	8	8	7	7	6	6
	$m = 3$	8	7	7	7	6	6	5	5	5	4
	$m = 2$	n/a	5	5	5	5	4	4	3	3	3
$r = 2$	$m = 5$	9	8	8	8	7	7	6	6	5	5
	$m = 4$	n/a	7	7	6	6	6	5	5	4	4
	$m = 3$	n/a	n/a	5	5	5	4	4	4	3	3
	$m = 2$	n/a	n/a	n/a	n/a	3	3	3	2	2	2

Abbreviations: α= Type I decision error limit; *r* = number of cycles; *m* = number of ranking cycles.

Table E.5. Critical Values for the Simple Random Sampling Sign Test

n	α								
	0.005	**0.01**	**0.025**	**0.05**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
45	31	30	29	28	27	25	24	23	22
44	30	30	28	27	26	25	24	23	22
43	30	29	28	27	26	24	23	22	21
42	29	28	27	26	25	24	23	22	21
41	29	28	27	26	25	23	22	21	20
40	28	27	26	25	24	23	22	21	20
39	27	27	26	25	23	22	21	20	19
38	27	26	25	24	23	22	21	20	19
37	26	26	24	23	22	21	20	19	18
36	26	25	24	23	22	21	20	19	18
35	25	24	23	22	21	20	19	18	17
34	24	24	23	22	21	19	19	18	17
33	24	23	22	21	20	19	18	17	16
32	23	23	22	21	20	18	17	17	16
31	23	22	21	20	19	18	17	16	15
30	22	21	20	19	19	17	16	16	15
29	21	21	20	19	18	17	16	15	14
28	21	20	19	18	17	16	15	15	14
27	20	19	19	18	17	16	15	14	13
26	19	19	18	17	16	15	14	14	13
25	19	18	17	17	16	15	14	13	12
24	18	18	17	16	15	14	13	13	12
23	18	17	16	15	15	14	13	12	11
22	17	16	16	15	14	13	12	12	11
21	16	16	15	14	13	12	12	11	10
20	16	15	14	14	13	12	11	11	10
19	15	14	14	13	12	11	11	10	9
18	14	14	13	12	12	11	10	10	9
17	14	13	12	12	11	10	10	9	8
16	13	13	12	11	11	10	9	9	8
15	12	12	11	11	10	9	9	8	7
14	12	11	11	10	9	9	8	7	7
13	11	11	10	9	9	8	7	7	6
12	10	10	9	9	8	7	7	6	6
11	10	9	9	8	8	7	6	6	5
10	9	9	8	8	7	6	6	5	5
9	8	8	7	7	6	6	5	5	4
8	7	7	7	6	6	5	5	4	4
7	7	6	6	6	5	5	4	4	3
6	6	6	5	5	5	4	4	3	3
5	5	5	5	4	4	3	3	3	2
4	4	4	4	4	3	3	3	2	2

Abbreviations: α= Type I decision error limit; n = number of laboratory samples.

Example 4 illustrates the application of the RSS Sign Test to the data in **Example 1**.

Example 4: Example of Ranked Set Sampling Data Used with the Sign Test

The $DCGL_W$ for our earlier example is 40 Bq/kg. Under Scenario A, the null hypothesis is that the median of the underlying population is greater than or equal to the $DCGL_W$. If the tolerable Type I error probability is 0.025, then the critical value is 9. The test statistic, S^{+}_{RSS}, is calculated by counting the number of samples with concentrations below the $DCGL_W$.

Sample No.	*k*	*i*	$X_{[k]i}$	$D_{[k]i}$	Sign($D_{[k]i}$)
1	1	1	32.0	8.0	+1
2	1	2	33.2	6.8	+1
3	1	3	38.4	1.6	+1
4	2	1	36.8	3.2	+1
5	2	2	37.2	2.8	+1
6	2	3	35.2	4.8	+1
7	3	1	34.0	6.0	+1
8	3	2	34.4	5.6	+1
9	3	3	39.6	0.4	+1
10	4	1	31.6	8.4	+1
11	4	2	35.6	4.4	+1
12	4	3	43.2	−3.2	−1
					S+ = 11

Abbreviations: $X_{[k]i}$ = data for the kth set, ith sample; $D_{[k]i}$ = Difference between the $DCGL_W$ and the $X_{[k]i}$; S+ = Statistic for the Sign Test.

Because the concentration in 11 of the 12 samples were less than $\mathrm{DCGL_W}$, $S^{+}_{\mathrm{RSS}} = 11$. Since the test statistic, S^{+}_{RSS}, was greater than the critical value, the null hypotheses that the median of the underlying population is greater than or equal to the $\mathrm{DCGL_W}$ is rejected.

E.3 Summary Example of a Final Status Survey Using Ranked Set Sampling

In **Example 5**, the design of a survey for an HTD radionuclides is provided, modified from Vitkus (2012).

Example 5: Example of a Survey Design for Hard-to-Detect Radionuclides Using Ranked Set Sampling

To illustrate the concept, an example using technetium-99 (^{99}Tc) will be provided. This approach may be used for HTDs in soil with minor preparations. The required method would use an alpha- or beta-sensitive detector as appropriate for performing the field screening counts that meets the established MQOs for the screening measurement (See **Section E.1.5**). A 100-gram sample of the surface soil would be collected from each investigation location, shaken in a container for size reduction of the soil, and then placed into a jig for consistent geometry. A 1-minute alpha and/or beta measurement is performed and the resultant counts ranked. The ranking provides the bases for selecting samples for laboratory analysis according to the following procedures. The intent is not to expect a direct correlation between counts and concentration, only the relative ranking.

Field Application Parameters:

1. **Statistical Test:** Many HTD radionuclides, including ^{99}Tc, will not be present at significant concentrations relative to background, and in most cases the DCGLs would be expected to be several times, or orders of magnitude, greater than background. For this reason, the sign test is selected.
2. **Survey boundaries:** Generally, for Class 1 survey units, boundaries should be selected to limit the size of the survey unit to no more than 2,000 square meters (m^2). For this example, survey unit, the size of the survey unit is 2,000 m^2.
3. **HTDs:** The utility of the process has been confirmed for alpha-emitters in soil and beta-emitters in soil where the β_{max} energy is greater than ~250 kilo-electron-volt (e.g., ^{99}Tc and strontium-90 are two of the more common beta-emitting HTDs encountered).
4. **RSS ranking limitations (minimum ranking capability):** To reliably rank samples, concentrations of 185 to 370 Bq/kg (5 to 10 picocuries per gram [pCi/g]) alpha HTD concentration of radioactive material and 3,700 to 7,400 Bq/kg (100 to 200 pCi/g) for lower energy beta-emitting HTD (^{99}Tc), and lower concentrations for higher energy beta-emitters are generally required. The minimum ranking capability is the lowest concentration of radioactive material that will be consistently greater than the instrument/background soil count rate and, therefore, result in the ability to use professional judgment to rank a given count as low, medium, or high when varying HTD concentrations of radioactive material are truly present. This ranking limitation is used for comparison to the applicable $DCGL_{EMC}$.
5. **Decision error limits:** The Type I decision error limit is set at 0.05 for the example. The Type II decision error limit is also set at 0.05 for the example. MARSSIM provides all necessary considerations for controlling the decision errors. However, an additional error must also be controlled: the probability (p) of detecting an area of elevated concentration of radioactive material of a given size. Acceptable risk of not detecting an area of elevated concentration of radioactive material of a given size is defined as $(1 - p)$.
6. **Survey design parameters:** FSS survey design optimization examples are as follows for ^{99}Tc. The $DCGL_W$ is 725 Bq/kg (19.6 pCi/g). Area factors and $DCGL_{EMC}$s are provided in the table below. The survey unit mean and standard deviation are 355 and 185 Bq/kg (9.6 and 5 pCi/g), respectively.

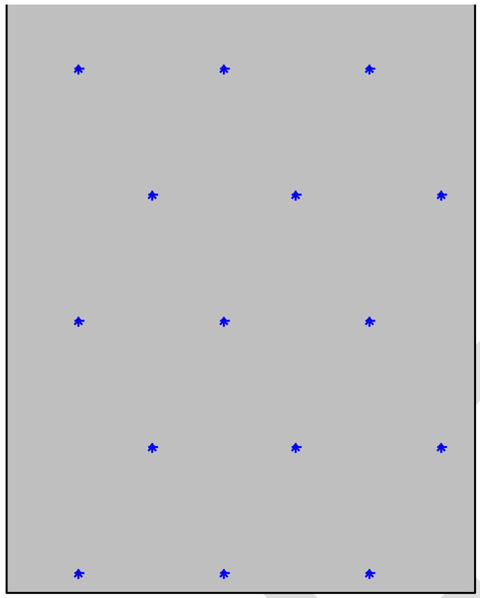
^{99}Tc $DCGL_{EMC}$ Information					
Area Factors	10 m^2	20 m^2	50 m^2	100 m^2	200 m^2
	74.6	43.9	21.1	11.6	6.2
$DCGL_{EMC}$ (Bq/kg)	54,100	31,800	15,300	8,400	4,480
$DCGL_{EMC}$ (pCi/g)	1,462	860	413	227	121

Abbreviations: 99Tc = technetium-99; DCGL = Derived Concentration Guideline Level; EMC = elevated measurement comparison; Bq/kg = becquerels per kilogram; pCi/g = picocuries per gram.

7. **Number of samples required:** Using **Table 5.5**, these planning parameters ($\Delta/\sigma = 2.0$) result in 15 samples necessary for the SRS sign test.

Field Application Example Procedure:

1. The 15 samples are distributed in the survey unit as shown below.



2. The planning team evaluates this sample plan relative to historical information and characterization data. The largest un-sampled area for this current plan is 133 m^2.

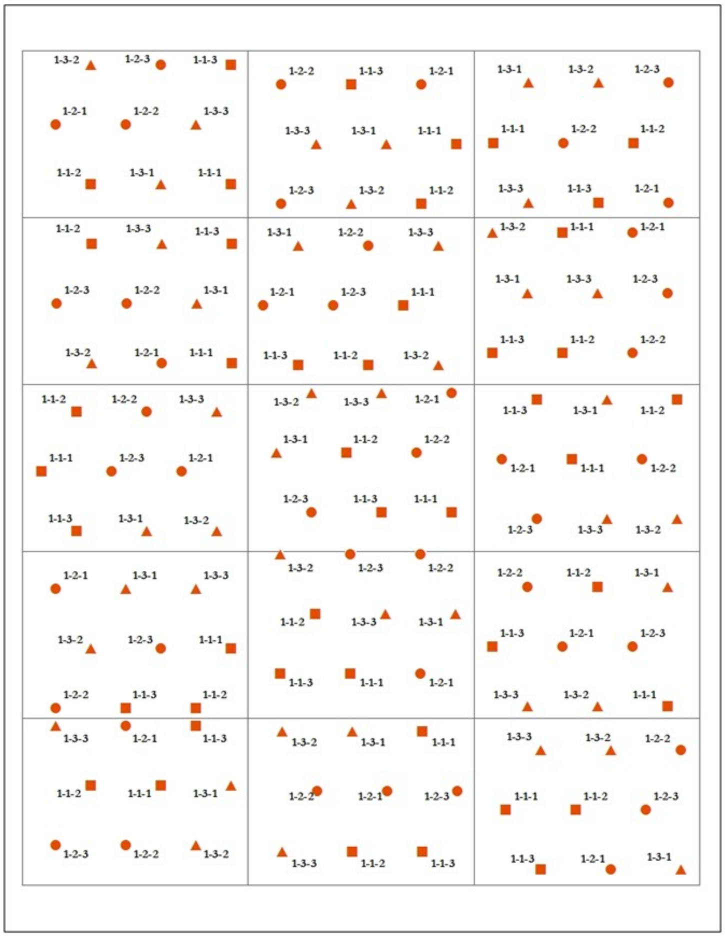
$$L = \sqrt{\frac{2000 \text{ m}^2}{(0.866)(15)}} = 12.4 \text{ m}$$
$$0.866 \times L^2 = 0.866 \times (12.4 \text{ m})^2 = 133 \text{ m}^2$$

3. Next, the size of the area of elevated concentrations of radioactive material of concern must be ascertained. The difficult question that must be answered at this point is: What is the appropriate maximum area of elevated concentration of radioactive material that should be considered in planning? For this example, assume the planning team examined the site characterization data as follows: (a) The full characterization data, consisting of 74 samples from Class 1 areas of the site, were used to determine a pre-site remediation 95 and 99 percent upper confidence level (UCL). The UCL results are 29,150 and 35,350 Bq/kg (787.9 and 955.4 pCi/g) respectively. (b) These results are compared with the maximum concentration identified during characterization to establish the acceptable maximum reasonable concentration following remediation. Of the 74 characterization samples, two exceeded the 99 percent UCL. Further evaluations also show that these two samples were collected from a known spill site.
4. This information is combined to propose that the maximum size of the area of elevated concentration of radioactive material concern will be based on the area factor that equates to the 35,350 Bq/kg (955.4 pCi/g) 99% UCL, and hence the associated $DCGL_{EMC}$. This concentration corresponds to an area factor of 48.7 (interpolated from the table above). This value is compared with the minimum ranking capability of 3,700 to 7,400 Bq/kg (100 to 200 pCi/g) and is readily discernible.
5. The area factor is interpolated between the bounding values provided in the table below and translates to an area of 17.4 m^2, meaning that an area of 17.4 m^2 with a concentration of 35,350 Bq/kg would not result in a dose or risk greater than the release criteria. To

ensure that largest un-sampled area is no larger than 17.4 m^2, the number of sample locations in a conventional MARSSIM survey would need to be increased. In this survey unit, 115 samples ($2000\ \mathrm{m}^2/17.4\ \mathrm{m}^2 = 115$) within the 2000 m^2 survey unit would be necessary to address areas of elevated concentrations of radioactive material of concern. The large increase in sample size from the statistically required 15 to 115 for consideration of areas of elevated concentration of radioactive material leads to the decision to use RSS as a means to reduce the total number (115) of samples requiring laboratory analysis.

6. For simplicity, the original 15 sampling locations will form the basis for RSS design subunits.[3]
7. The number of sample locations is adjusted as necessary to allow for one complete RSS cycle of three sets ($m^2 = 9$ investigation locations for one cycle) within each subunit. For this example, the number is increased from 115 to 135 (15 subunits with nine investigation locations each), which also further reduces the sample spacing to 14.8 m^2. The net result is that by using RSS, a total of 135 field screening measurements will be made, while the number of laboratory samples is reduced to 45 (three laboratory samples from each of the 15 subunits).

[3] Note that if one calculates the number using **Table E.3,** only 12 samples would be required—the decrease is a result of the increase in power from using RSS instead of SRS. However, the sample spacing would still need to be increased to account for areas of elevated activity, hence the 115 samples calculated by SRS accounting for areas of elevated activity is increased to 135 to ensure that the sample spacing is still sufficiently small.



Squares: Set 1 (lowest measurement location from Set 1 sampled in each composite sample unit.)

Circles: Set 2 (medium measurement location sampled).

Triangles: Set 3 (highest measurement location sampled).

8. For each of these subunits, these nine RSS locations (one cycle of three sets for this example) for each subunit are randomized then distributed within each subunit on a random-start/systematic basis. The figure above shows the revised plan with the RSS investigation locations.
9. A pre-defined quantity of soil, nominally 100 grams, is collected from each RSS location, processed to break the soil up, and placed within a reproducible geometry that matches the physical area of an alpha or beta detector, with the preferred detector area of at least 100 square centimeters.
10. A 1-minute alpha or beta measurement—dependent on whether the HTD is an alpha- or beta-emitter—is performed at each RSS location and the results recorded. For this example, with ^{99}Tc as the HTD, beta measurements are performed.

11. The measurement results are ranked within each subunit using the “low” (L), “medium” (M) or “high” (H) count for each “cycle-set-location”. The table below shows what these results may look like for a subunit.

Cycle-Set-Map Code	Beta Measurement (cpm)	Sample Select/ID L=Low, M=Medium, H=High
1-1-1 ■	1,750	L
1-1-2 ■	538	L/Sample 1
1-1-3 ■	615	L
1-2-1 ▲	524	M
1-2-2 ▲	820	M
1-2-3 ▲	578	M/Sample 2
1-3-1 ●	557	H
1-3-2 ●	620	H
1-3-3 ●	1,041	H/Sample 3

Abbreviations: cpm = counts per minute.

12. The process is continued until all subunits have been measured and sampled in accordance with the RSS process. The RSS-selected samples are submitted for laboratory analysis and the MARSSIM data quality assessments performed, including application of the RSS sign test. The net result is that 15 laboratory samples were required for the SRS sign test, but the requirements were increased to 45 laboratory samples to account for areas of elevated concentration of radioactive material that could reasonably be expected. This process closely parallels the more familiar required/actual scan MDC paradigm used successfully for MARSSIM soil surveys involving gamma-emitting radionuclides.
13. NOTE: Additional judgmental samples may be collected from elevated measurement locations within each subunit, including additional real-time investigations of the contiguous area. For example, in the table above, the lowest measurement location is sampled in Cycle 1-Set 1 to provide the statistical data for estimating the survey unit mean concentration and in performance of the sign test. However, the obvious anomalous measurement at location 1-1-1 would be judgmentally sampled and the analytical result compared directly with the $DCGL_{EMC}$.
14. Lastly, the probability for the detection of areas of elevated concentration of radioactive material smaller than those for which the plan was initially designed—discussed in Step 3—will now be defined. The design basis of the above example provides a probability of 0.9998 (99.98%) that an elliptically shaped area of elevated concentration of radioactive material with a semi-major axis of 2.7 meters and length to width ratio of 0.8 (18.3 m^2) would be sampled as an RSS location. Conversely, this equates to a risk of $1 - p$, or 0.0002 (0.02%). The probability of detecting smaller areas of elevated concentration of radioactive material can also be calculated. For example, the probability for detection of a 10 m^2 elliptical area of elevated concentration of radioactive material using this example survey design decreases to 0.6792 (67.92%). Perhaps a size of the area of elevated concentration of radioactive material between these two examples that corresponds to a 95 percent ($p = 0.95$) detection probability would be agreeable. In any event, discussions and data sharing with the regulatory agency will be necessary to conclude whether such a condition could exist or agree on an acceptable risk (defined as $1 - p$) of an area of elevated concentration of radioactive material not being sampled that is smaller than those assured of detection by the RSS design considerations. The survey design could then be augmented with additional RSS subunits to achieve the acceptable

spacing and corresponding detection capability of an area of elevated concentration of radioactive material.

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 presents a discussion of the relationship between the Radiation Survey and Site Investigation (RSSI) 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 (DQO) Process and data interpretation using Data Quality Assessment (DQA) 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 or Corrective Measure 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 (RD/RA) step of the CERCLA Remedial Process described in § 300.435(b)(1) of Part 40 of the Code of Federal Regulations. However, MARSSIM's focus is not directly addressed by the major steps of the CERCLA Removal Process or 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 1991e) 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, EPA 1994b). However, MARSSIM includes scanning for radioactive material that 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.

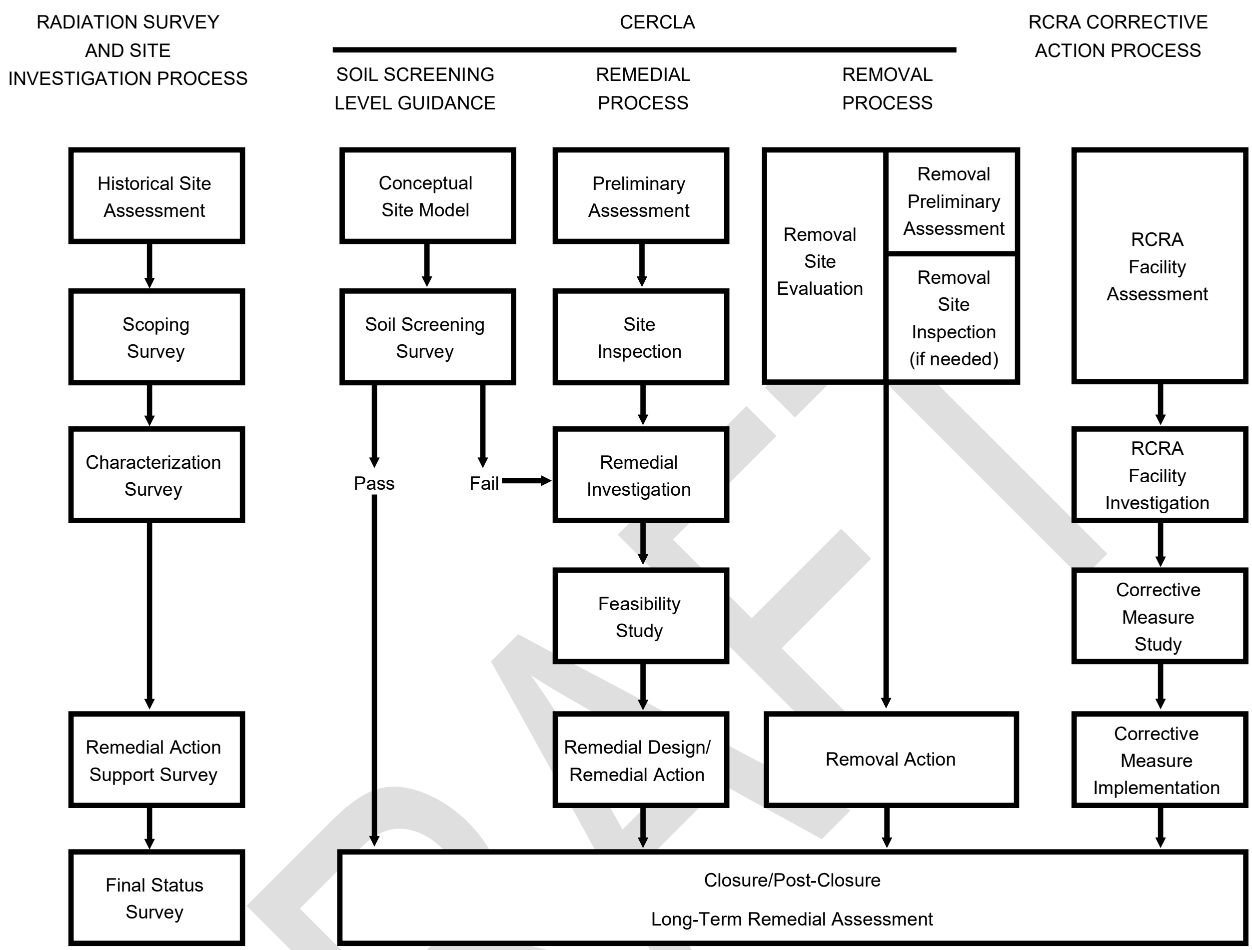


Figure F.1: Comparison of the Radiation Survey and Site Investigation Process with the CERCLA Superfund Process and the RCRA Corrective Action Process

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 between 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 multi-agency consensus technical document.

The first step in the CERCLA Remedial Process is the Preliminary Assessment to obtain existing information about the site and determine if 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, a Field Sampling Plan, a Health and Safety

Plan, and a Community Relations Plan. The site Feasibility Study (FS) is the next step in the CERCLA Remedial Process (although the RI and FS are intended to be done concurrently), which involves an evaluation of alternative remedial actions. For sites listed on the NPL, the next action would be to obtain a Record of Decision (ROD), which provides the remedy selected for the site. The Remedial Design/Remedial Action (RD/RA), which includes the development of the selected remedy and its implementation, follows development of the ROD. After the RD/RA activities there is a period of operation and maintenance when the site is given a long-term remedial assessment followed by closure/post-closure 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 Remedial Process for the first few steps. The National Contingency Plan Subpart E—Hazardous Substance Response (40 CFR § 300.400) 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 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 make the determination of whether a Removal Action is necessary. A Removal Site Inspection is performed, if warranted, in a similar manner as 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 Quality Assurance Project Plan. 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 § 300.415, 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.

Comparisons have been made between the CERCLA Remedial Process and CERCLA Removal Process (EPA 1993b). **Table F.2** presents the data elements that are common to both programs and those that are generally common to one program rather than 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 Soil Screening Guidance (EPA 1996a, EPA 1996b), its supplement (Supplemental Guidance for Developing Soil Screening Levels at Superfund Sites, EPA 2002c), and 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. The combined Soil Screening Guidance (SSG) documents lead the user from the initial site conceptualization and

[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.

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 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—recommendations for the sampling grid size, the number of soil samples collected from each subarea and composited, and data analysis and interpretation techniques are described in detail. 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 sites as Action Levels (ALs). The RCRA Corrective Action program views ALs 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 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 that 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, 2007b, 2010). A memorandum from EPA, DOE, and DOD (August 22, 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
<u>Historical Site Assessment</u> Performed to gather existing information about radiation sites. Designed to distinguish between sites that possess no potential for residual radioactive material from those that require further investigation. Performed in three stages: 1. Site Identification 2. Preliminary Investigation 3. Site Reconnaissance	<u>Preliminary Assessment</u> Performed to gather existing information about the site and surrounding area. The emphasis is on 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 from sites that require further investigation.	<u>Preliminary Assessment</u> Performed in a similar manner as in the CERCLA Remedial Process. The Removal Preliminary Assessment may be based on available information. A Removal Preliminary Assessment 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 an evaluation of factors to determine if a Removal Action is necessary.	<u>RCRA Facility Assessment (RFA)</u> 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 RFA accomplishes the same objectives as the CERCLA Preliminary Assessment and Site Inspection. The RFA often forms the basis for the first conceptual model of the site.
<u>Scoping Survey</u> 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.	<u>Site Inspection</u> 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.	<u>Site Inspection</u> Performed in a similar manner as in the Remedial Process. A removal site inspection may be performed as part of the Removal Site Evaluation (§ 300.410) if warranted. A Removal Site Inspection may include a perimeter or on-site inspection. If the removal site evaluation shows that a Removal Action is not required, but that Remedial Action under § 300.430 may be	

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA
		necessary, a Remedial Site Evaluation pursuant to § 300.420 would be initiated.	
<u>Characterization Survey</u> Performed to support planning for Final Status Surveys 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 Remedial Investigation/ Feasibility Study (RI/FS) and Facility Investigation/ Corrective Measure Study (FS/CMS).	<u>Remedial Investigation (RI)</u> 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. 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	<u>Removal Action</u> Performed once the decision has been made to conduct a Removal Action at the site (under § 300.415). Whenever a planning period of at least 6 months exists before on-site activities must be initiated, an engineering evaluation/cost analysis or its equivalent is conducted. 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: 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 Quality Assurance Project Plan (QAPP), which describes the policy,	<u>RCRA Facility Investigation (RFI)</u> 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: 1. Characterize the potential pathways of contaminant migration 2. Characterize the source(s) of contamination 3. Define the degree and extent of contamination 4. Identify actual or potential receptors 5. Support the development of alternatives from which a corrective measure will be selected by EPA The RFI is performed in seven tasks: 1. Description of current conditions

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA
	2. Field investigations 3. Sample/analysis verification 4. Data evaluation 5. Assessment of risks 6. Treatability study/pilot testing 7. RI reporting	organization, functional activities, measures, and Data Quality Objectives necessary to achieve adequate data for use in the Removal Actions.	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
DCGLs Residual concentration levels of radioactive material that correspond to allowable radiation dose or risk standards that are calculated (derived concentration guideline levels, or DCGLs) and provided to the user. The Survey Unit is then evaluated against this radionuclide-specific DCGL.	PRGs Preliminary Remediation Goals (PRGs) are 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. Soil Screening Levels (SSLs) can be used as PRGs provided 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	Removal Levels The Removal Level is established by identifying applicable or relevant and appropriate requirements (ARARs), 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 (ALs) 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 ALs because the RCRA

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA
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.	based on 10^{-6} risk for carcinogens and a Hazard Index Quotient of 1 for non-carcinogens (using child ingestion assumptions); or Maximum Contaminant Level Goals, Maximum Contaminant Levels, or Health-Based Levels for contaminant migration into groundwater. The User's Guide provides equations and guidance for calculating site-specific SSLs.		Corrective Action Program currently views them as serving the same purpose.
No Direct Correlation (MARSSIM Characterization and Remedial Action Support surveys may provide data to the Feasibility Study or the Corrective Measure Study)	<u>Feasibility Study</u> The Feasibility Study (FS) 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. However, the FS is generally considered to be composed of four general tasks. These tasks are: 1. Development and screening of remedial alternatives 2. Detailed analysis of alternatives 3. Community relations 4. FS reporting	No Direct Correlation	<u>Corrective Measures Study</u> The purpose of the Corrective Measures Study (CMS) is to identify, develop, and evaluate potentially applicable corrective measures and to recommend the corrective measures to be taken. The CMS is performed following an RFI and consists of the following four tasks: 1. Identification and development of the corrective measures alternatives 2. Evaluation of the corrective measures alternatives 3. Justification and recommendations of the

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA
			corrective measures alternatives 4. Reports
<u>Remedial Action Support Survey</u> These surveys are performed to support remediation activities and determine when a site or survey unit is ready for the Final Status Survey. 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. Remedial Action Support Surveys do not include routine operational surveys that are conducted to support remedial activities.	<u>Remedial Design/Remedial Action</u> This activity 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 (RD/RA) activities. Generally, the RD/RA includes: 1. Plans and specifications • Preliminary design • Intermediate design • Pre-final/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	No Direct Correlation	<u>Corrective Measures Implementation</u> The purpose of the Corrective Measures Implementation (CMI) is to design, construct, operate, maintain, and monitor the performance of the corrective measures selected in the CMS. The CMI consists of four activities: 1. CMI Program Plan 2. Corrective measures design • Design plans and specifications • Operation and Maintenance Plan • Cost estimate • Schedule • Construction QA objectives • Health and Safety Plan • Design phases 3. Corrective measures construction (includes a construction QA program) 4. Reporting

MARSSIM	CERCLA REMEDIAL PROCESS	CERCLA REMOVAL PROCESS	RCRA
	4. QAPP 5. Site Safety Plan		
<u>Final Status Survey</u> Performed to demonstrate that residual radioactive material in each survey unit meets the release criteria.	<u>Long-Term Remedial Assessment</u> Closure/Post-Closure NPL De-Listing	<u>Post-Removal Site Control</u> Those activities that are necessary to sustain the integrity of a Removal Action following its conclusion.	<u>Closure/Post-Closure</u>

Table F.2: Data Elements for Site Assessments[a]

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 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

[a] From EPA 1993b.

Table F.3: Comparison of Sampling Emphasis between Remedial Site Assessment and Removal Site Assessment[a]

Remedial Site Assessment Emphasis	Removal Site Assessment Emphasis
• Attribution to the site • Background samples • Ground water 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 removal assessment • Strategic sampling for Hazard Ranking System	• Sampling from containers • Physical characteristics of wastes • Treatability and other engineering concerns • On-site contaminated soils • Composite and grid sampling • Rapid turnaround on analytical services • Field/screening analyses • Potentially responsible party (PRP)-lead removal actions • Goal of characterizing site

• Contract Laboratory Program usage • Full screening organics and inorganics analyses • Definitive analyses • Documentation, including targets and receptors • Computing Hazard Ranking System scores • Standardized reports	• Focus on National Continency Plan removal action criteria

[a] From EPA 1993b

G HISTORICAL SITE ASSESSMENT INFORMATION SOURCES

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

- **Table G.1,** beginning on page G-2, 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:
  - Databases, p. G-2
  - Maps and Aerial Photographs, p. G-5
  - Files, p. G-7
  - Experts and Other Sources, p. G-8
- **Table G.2** beginning on page G-12, identifies information needs by category and lists some information sources for each. The categories are:
  - General Site Information, p. G-12
  - Source and Waste Characteristics, p. G-12
  - Ground Water Use and Characteristics, p. G-13
  - Surface Water Use and Characteristics, p. G-15
  - Soil Exposure Characteristics, p. G-16
  - Air Pathway Characteristics, p. G-17

More complete listings of site assessment information sources are available in the *Site Assessment Information Directory* (EPA 1991g).

1 **Table G.1: Site Assessment Information Sources (Organized by Information Source)**

Databases	
Source:	Superfund Enterprise Management System (SEMS)
Provides:	EPA's 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 (EPA) Office of Land and Emergency Management (OLEM) [formerly known as Office of Solid Waste and Emergency Response (OSWER)] https://www.epa.gov/enviro/sems-search
Source:	RODS (Records of Decision System)
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, Source and Waste Characteristics
Contact:	U.S. Environmental Protection Agency Office of Land and Emergency Management (OLEM) [formerly known as Office of Solid Waste and Emergency Response (OSWER)] https://www.epa.gov/superfund/search-superfund-decision-documents
Source:	Envirofacts
Provides:	EPA's 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, Source and Waste Characteristics
Contact:	U.S. Environmental Protection Agency Office of Land and Emergency Management (OLEM) [formerly known as Office of Solid Waste and Emergency Response (OSWER)] 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:	Ground Water Use and Characteristics
Contact:	National Ground Water Association (NGWA) 601 Dempsey Rd. Westerville, OH 43081 https://www.ngwa.org/about/Contact-NGWA
Source:	Water Quality Portal (WQP)
Provides:	EPA's repository of water quality data for waterways within the U.S. The system can perform a broad range of reporting, statistical analysis, and graphics functions.

Databases	
Supports:	Geographic and descriptive information on various waterways; analytical data from surface water, fish tissue, and sediment samples; stream flow data.
Contact:	U.S. Environmental Protection Agency Office of Water Office of Wetlands, Oceans, and Watersheds https://www.waterqualitydata.us/
Source:	USGS Water Data for the Nation
Provides:	U.S. Geological Survey's (USGS) National Water Data Storage and Retrieval System. Administered by the Water Resources Division and contains the Ground Water Site Inventory file (GWSI). This provides physical, hydrologic, and geologic data about test holes, springs, tunnels, drains, ponds, other excavations, and outcrops.
Supports:	General Site Information, Ground Water Use and Characteristics, Surface Water Use and Characteristics
Contact:	U.S. Geologic Survey 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:	U.S. Environmental Protection Agency National Analytical Radiation Environmental Laboratory http://www.epa.gov/radnet/
Source:	DENIX
Provides:	Inventory Databases for the Formerly Used Defense Sites (FUDS), Defense Environmental Restoration Program (DERP), and Military Munitions Response Program (MMRP).
Supports:	Site histories and processes, previous remedial activities, current remediation status
Contact:	DoD Environment, Safety and Occupational Health Network and Information Exchange https://www.denix.osd.mil/
Source:	NRC Agency-wide Document 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

Maps and Aerial Photographs	
Source:	U.S. Topo: Maps for America
Provides:	Maps detailing topographic, geographical, 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; karst terrain features
Contacts:	U.S. Geologic Survey National Geospatial Program https://www.usgs.gov/core-science-systems/ngp/tnm-delivery/topographic-maps
Source:	National Wetlands Inventory Maps
Provides:	Maps delineating boundaries and acreage of wetlands.
Supports:	Environmental setting and wetlands locations
Contact:	U.S. Geological Survey or U.S. Fish and Wildlife Service https://www.fws.gov/wetlands/data/Mapper.html
Source:	Flood Insurance Rate Map (FIRM)
Provides:	Maps delineating flood hazard boundaries for flood insurance purposes.
Supports:	Flood frequency
Contact:	Federal Emergency Management Agency (FEMA) Federal Insurance Administration Office of Risk Assessment 500 C Street, SW Washington, DC 20472 or Local Zoning and Planning Office
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, 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:	Contact: U.S. Geologic Survey National Cooperative Geologic Mapping Program https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html

Maps and Aerial Photographs	
Source:	Aerial Photographs
Provides:	Black and white and/or 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, 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's Environmental Photographic Interpretation Center (EPIC) U.S. Army Corps of Engineers U.S. Department of Agriculture, U.S. Forest Service U.S. Geological Survey U.S. Department of Energy U.S. Nuclear Regulatory Commission U.S. Department of the Interior (and Bureaus)
Source:	EarthExplorer
Provides:	An interactive computer system about the Earth's land surfaces information. EarthExplorer supports the searching of satellite, aircraft, and other remote sensing inventories through interactive and textual-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; karst terrain features
Contact:	U.S. Geologic Survey 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 data base 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, 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:	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 upon the stage of remediation at the site).
Source:	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.

Files		
Source:	EPA Regional Libraries	
Provides:	Historical information on CERCLIS sites, permits, violations, and notifications. Additionally, 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 16th Floor New York, NY 10007-1866 212/637-3185 USEPA Region 3 Library Second Floor (3MD50) 1650 Arch Street Philadelphia, PA 19103 215/814-5254 USEPA Region 4 Library Atlanta Federal Center 61 Forsyth Street, SW Atlanta, GA 30303-8909 404/562-8190 USEPA Region 5 Library 77 W. Jackson Blvd. Metcalfe Federal Building, 16th Floor Chicago, IL 60604-3590 312/886-1492	USEPA Region 6 Library 1445 Ross Avenue, Suite 1200 First Interstate Bank Tower Dallas, TX 75202-2733 214/655-6424 USEPA Region 7 Library 11201 Renner Road Lenexa, Kansas 66219 913/551-7979 USEPA Region 8 Technical Library 1595 Wynkoop Street, 8MSD/IMI Denver, CO 80202-1129 303/312-7226 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, OMP-0102 Seattle, WA 98101 206/553-1289

Experts and Other Sources	
Source:	U.S. Geological Survey
Provides:	Geologic, hydrogeologic, and hydraulic information including maps, reports, studies, and databases.
Supports:	General stratigraphy descriptions, karst terrain, depth to aquifer, stream flow, and ground water and surface water use and characteristics.
Contact:	U.S. Geological Survey or USGS Regional or Field Office 12201 Sunrise Valley Drive Reston, VA 22092
Source:	U.S. Army Corps of Engineers
Provides:	Records and data surrounding engineering projects involving surface waters.
Supports:	Ground water 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 ground water 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; surface water characteristics and stream flow.
Contact:	U.S. Fish and Wildlife Service or U.S. Fish and Wildlife Service Regional office 1849 C Street, NW Washington, DC 20240

Experts and Other Sources	
Source:	Local Fish and Wildlife Officials
Provides:	Local environmental information.
Supports:	Locations of sensitive environments, wetlands, and fisheries; surface water characteristics and stream flow.
Contact:	State or Local Environmental Agency State or Local Game or Conservation Office
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 regarding 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, ground water and surface water characteristics, and stream flow.
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 regarding 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

Experts and Other Sources	
Source:	Local Fire Department
Provides:	Records of underground storage tanks in the area, material safety data sheets (MSDS) 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.
Source:	Local University or College
Provides:	Geology/Environmental Studies departments may have relevant published materials (reports, theses, dissertations) and faculty experts knowledgeable in local geologic, hydrologic, and environmental conditions.
Supports:	General stratigraphic information, ground water and surface water use and characteristics, and stream flow.
Source:	Site Reconnaissance
Provides:	Onsite and/or offsite visual observation of the site and surrounding area.
Supports:	General site information; source identification and descriptions; general ground water, 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 U.S. Department of Defense (DOD) Facility Records U.S. Department of Energy (DOE) Facility Records	**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 Leases	**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	
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 Leases CERCLA and RCRA Administrative Records	

Ground Water Use and Characteristics	
General Stratigraphy USGS Topographic Maps U.S. Geological Survey 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 Leases 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 USGS Water Data for the Nation NRC or Agreement State Records DOD Facility Records DOE Facility Records Mineral Leases CERCLA and RCRA Administrative Records

Ground Water Use and Characteristics	
Karst Terrain U.S. Topo: Maps for America U.S. Geological Survey 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 Leases 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 USGS Water Data for the Nation Site Reconnaissance NRC or Agreement State Records DOD Facility Records DOE Facility Records Mineral Leases CERCLA and RCRA Administrative Records
Depth to Aquifer U.S. Geological Survey 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 Leases 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 Leases 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 Leases 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 Leases
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Surface Water Flow Characteristics U.S. Geological Survey 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 Leases 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 Leases CERCLA and RCRA Administrative Records

Surface Water Use and Characteristics	
Flood Frequency at the Site Federal Emergency Management Agency State Environmental Agency	

Soil Exposure Characteristics	
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Number of Workers Onsite 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 Leases CERCLA and RCRA Administrative Records

Air Pathway Characteristics	
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H DESCRIPTION OF FIELD SURVEY AND LABORATORY ANALYSIS EQUIPMENT

H.1 Introduction

This appendix provides information on various field and laboratory equipment used to measure radiation levels and radioactive material concentrations. The descriptions provide general guidance, and those interested in purchasing or using the equipment are encouraged to contact vendors and 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. Each system in this appendix has one or two pages of information, including its type of use (field or lab), the primary and secondary radiation detected, applicability for site surveys, operation, specificity/sensitivity, efficiency, and cost of the equipment and surveys performed.

The Applicability for Site Surveys section discusses how the equipment is most useful for performing site radiological surveys. The Operation section provides basic technical information on what the system includes, how it works, how to use it practically in the field, and what its features are. The Specificity/Sensitivity section addresses the system's strengths, weaknesses, and the concentrations of radioactive material it can measure. Information for the cost section was obtained primarily from discussions with manufacturers and users and reviews of product literature. The cost per measurement is an estimate of the cost of producing and documenting a single data point, generally as part of a multipoint survey. It assumes times for instrument calibration (primarily if conducted at the time of the survey), use, sample analysis, and report preparation and review. It should[1] be recognized that these values will change over time due to such factors as new technologies, inflation, and market expansion.

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

[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.

    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 via 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 are 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 a digital survey meter as they have an automatic scaling system.

  - **The interconnecting cables** serve to transfer the high voltage and detector signals in the proper direction. 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 allow the user to interchange detectors. Older systems require that the meter be turned off before cables (detectors) are switched. Newer systems do not require turning the meter off and users can switch the probes at any time – a process called a 'hot swap.' Some instruments might be equipped with Bluetooth (BT) connections. That allows probes to transmit data signal to the receptors, such as BT- equipped computers, phones or planchets.

- *Scanning and measuring surveys:* In a scanning survey, the field survey meter is operated while moving the detector 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:* Where additional sensitivity 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 sensitivity 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) in terms of unit time (e.g., counts per minute [cpm], mR/hour [h], or μR/h). Those with International System (SI) meter faces use units of millisievert (mSv), microsievert (μSv) or milligray (mGy) per unit time (e.g., mSv, μSv/h or mGy/h).

Tables H.2–H.7 are included at the end of the appendix and summarize the description, application, and costs 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 sensitive area of approximately 50–100 square centimeters (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)). When the discriminator is appropriately adjusted, the meter is sensitive only to alpha radiation. Light pulses are amplified by a photomultiplier tube and passed to the survey meter. Newer alpha/beta survey meters incorporate the ZnS(Ag) detection medium, adhered to a plastic scintillator that is approximately 0.25 millimeters (mm; 0.01 in.) thick to provide both alpha and beta detection capability in one survey meter. The probe is generally placed close to the surface due to 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 sensitivity 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 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 only 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. Alpha radiation is easily absorbed by irregular, porous, moist, or painted surfaces; this should be carefully considered when converting count rate data to concentrations of radioactive material on surfaces. The minimum sensitivity 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, etc.), so the manual should be consulted to preclude underestimating the concentration of radioactive material.

Approximate Cost of Equipment: $2,000–$4,000
Approximate Cost per Measurement: $10

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 (~75–200 cm^2 open area) are hand-held, and large detectors (~400–600 cm^2 open area) are mounted on a rolling cart. The detector entrance window can be < 1 milligram [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 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, efficiencies range from 5 percent for highly attenuated to about 35 percent for unattenuated sources. Typical gamma ray efficiency is < 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 using the quick disconnect fittings can cause count rate instability.

Approximate Cost of Equipment: $2,000–$5,000
Approximate Cost per Measurement: $5–$15/square meter (m^2)

H.2.2 Beta Particle Detectors

System: Alpha-Beta Scintillation Survey Meter (See Section H.2.1)

System: Gas-Flow Proportional Counter (See Section H.2.1)

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. 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 through 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 such emitters as hydrogen-3 (^{3}H, 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 efficiency at a field site is primarily a function of the beta energy, window thickness, and surface condition. The detection sensitivity can be improved by using headphones or the audible response during scans, 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 sensitivity and eliminate the need to swipe. The sensitivity to gamma radiation is about 10 percent or less of the beta sensitivity, but the alpha detection efficiency is difficult to evaluate.

Approximate Cost of equipment: \$800–\$2,000
Approximate Cost per Measurement: \$5–\$10 per location

H.2.3 Gamma Ray Detectors

System: Hand-Held 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 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. Due to 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 units of readout are 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 h of operation.

Specificity/Sensitivity: Sealed ion chamber instruments respond only to gamma or x-radiation. They have no means to provide the identity of radionuclides. Typical ion chamber instruments have a lower limit of detection of 0.5 mR/hr. 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 sensitivity can be as low as 0.05 mR/hr.

Approximate Cost of Equipment: $1,000–$1,800
Approximate Cost per Measurement: $10, or higher for making integrated exposure measurements.

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

Applicability to Site Surveys: The hand-held pressurized ion chamber survey meter measures 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. Due to their high detection limit, these instruments are not applicable for many FSSs.

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 increase the sensitivity of the instrument by the same factors. 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. The unit may use two D-cell batteries or a 9 V battery that will last for 100–200 h of operation.

Specificity/Sensitivity: Because the ion chamber is sealed, pressurized ion chamber instruments respond only to gamma or x-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.

Approximate Cost of Equipment: $1,000–$1,500
Approximate Cost per Measurement: $5, or higher for making integrated exposure measurements.

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

Applicability to Site Surveys: The pressurized ionization chamber (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 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-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.

Approximate Cost of Equipment: $15,000–$50,000, depending on the associated electronics, data processing, and telecommunications equipment
Approximate Cost per Measurement: $50–$500 based on the operating time at each site and the number of measurements performed

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

Applicability to Site Surveys: This instrument is used to give a quick indication of gamma radiation levels present at a site. Due to 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 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 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. Conversion from count rate to exposure rate is accomplished 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 “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-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 sensitivity 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 sensitivity 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 sensitivity. 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 sensitivity may be reduced.

Approximate Cost of Equipment: $800–$2,000.
Approximate Cost per Measurement: $10 per measurement for survey and report.

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

Applicability to Site Surveys: Sodium iodide (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.

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 pressurized ion chamber 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 listening to the audio, watching the display for changes, or in 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 a sodium iodide crystal inside an aluminum container with an optical glass window that is connected to a photomultiplier tube. A gamma ray that interacts with the crystal produces scintillations that travel out of the crystal and into the photomultiplier tube. There, electrons are produced and multiplied to produce a readily measurable pulse whose magnitude is proportional to the energy 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 sensitivity of about 1–5 μR/h (200–1,000 cpm) or lower in digital integrate mode. When utilizing 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 25 mm (1 in.) x 25 mm (1 in.) to 75 mm (3 in.) x 75 mm (3 in.) The typical instrument utilized for environmental surveys is a 50 mm (2 in.) x 50 mm (2 in.). Each are 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 photomultiplier tube. Covering at least the crystal end with padding is often sufficient.

Approximate Cost of Equipment: $2,000
Approximate Cost per Measurement: $5

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

Applicability to Site Surveys: Lanthanum bromide (LaBr) survey meters are useful for identifying radionuclides and produce semi-quantitative estimates of gamma-emitting isotopes in various media. LaBr offers improved energy resolution and counting efficiency as compared to NaI survey meters and does not require the supporting infrastructure of high purity germanium detectors. Coupled with fast emission and excellent temperature and linearity characteristics, these survey meters utilize algorithms to allow a more accurate discrimination of energy peaks in ranges where isotopes often have many overlapping peaks.

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

Specificity/Sensitivity: Due to recent advances in growing LaBr scintillation crystals, the available ranges in size are comparable to NaI crystals and have demonstrated a high light output (~60,000 photons/megaelectron volt [MeV]) with a fast decay time. The response function of LaBr scintillators has been shown to be linear and improves with increase 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 NaI due to 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}]) due to intrinsic activity from ^{138}La and actinium-227 (^{227}Ac), leading manufacturers to improve crystal manufacturing and to utilize algorithms or other background suppression techniques to achieve suitable sensitivity required for detecting and measuring low-activity samples. Thus, the intrinsic photo-peak 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 NaI. LaBr is more hygroscopic than NaI, and the detector should be protected against thermal or mechanical shock, which can break the crystal or the photomultiplier tube.

Approximate Cost of Equipment: $10,000–$45,000
Approximate Cost per Measurement: $10–$50

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 which are useful for identifying radionuclides and can produce semi-quantitative estimates of gamma-emitting isotopes in a variety of media. Currently used primarily in medical, industrial and homeland security applications, CZT detectors are modular, offer excellent spectroscopic resolution, and can process more than 10 million photons s^{-1} mm^{-2}. Although not widely used in site surveys at present, the ability of a CZT detector to produce detector arrays that operate at room temperatures make it a potential candidate for wider applications in surveys of soil, buildings, and other materials affected by residual radioactive material.

Operation: CZT detectors are 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 where they are collected, amplified, and produce a signal proportional to the energy of the incoming radiation, which is fed into a multichannel analyzer to generate characteristic spectra.

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 to CZT is that the mobility and lifetime of the electrons and the holes are quite different. Due to their low mobility and short lifetime, holes are trapped very quickly and cannot contribute to the formation of a full energy signal. Consequentially, 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. The maximum volume of a single element detector is presently limited to about 2.3 cm^3. Detector arrays are being constructed to increase the detector volume, but cost can be an inhibiting factor to wider applications.

Approximate Cost of Equipment: $10,000–$60,000
Approximate Cost per Measurement: $10–$60

System: Portable Germanium Multichannel Analyzer System
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** Neutrons

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 isotopes concentrations in soil.

Operation: This system consists of a portable high-purity germanium detector with cooler, high-voltage power supply and a multichannel analyzer (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 (lbs) 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 4–24 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 to 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 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 only be applied 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 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 milligrams (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 in the order of minutes, depending on the enrichment and the attenuating materials.

Approximate Cost of Equipment: $40,000–$80,000
Approximate Cost per Measurement: $100–$300

H.2.4 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-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 photomultiplier tube. 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 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. Typical sensitivities for ^{238}Pu and ^{239}Pu at 1 foot (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 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/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 to prevent damaging the window, such as styrofoam, cardboard, and other cushioning materials.

Approximate Cost of Equipment: $4,000–$7,000
Approximate Cost per Measurement: $10–$20

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 multichannel analyzer 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, the systems most frequently are only calibrated 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 sensitivity 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 ^{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.

Approximate Cost of Equipment: $15,000–$75,000, depending on size, speed of operation and auxiliary features employed for automatic analysis of the results
Approximate Cost per Measurement: $200

H.2.5 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 detectors 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, smaller (50 mm [2 in.] x 50 mm [2 in.]) NaI, or FIDLER detectors. Data is typically collected each second and is georeferenced using Global Positioning Systems (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 allows the distinction between natural background radiation levels and levels from the radionuclides of concern. Moreover, if spectral data is 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 systems geometry, efficiency, and scan speed. The scan MDC is calculated using fixed parameters in the survey plan to ensure the data quality objectives are met.

For a manually controlled system, typical scan speeds are 0.5–1.0 meters per second 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.) sodium iodide system, scan speed of 1 meter per second, 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 meter per second 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.

Approximate Cost of Equipment: $10,000–$100,000, depending on such parameters as detector and array size, electronics, software, etc.
Approximate Cost per Measurement: $70,000 per square kilometer (km^2) surveyed

System: Aerial Systems
Field/Laboratory: Field
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** Neutron

Applicability to Site Surveys: Surveys over large areas are conducted through a series of low-level flights utilizing a mounted array of high-efficiency detectors to identify and measure gamma and neutron 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 man-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 assure 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 a 12-detector system in a helicopter traveling at about 15 m (50 ft) AGL at about 36 m/s (70 knots) has been documented to be 13,000 Bq/m^2 (0.035 μCi/m^2) for surface distribution. By simply increasing flight altitude to approximately 90 m (300 ft) AGL, this same MDA value reduces to 0.0082 μCi/m^2, respectively.

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 12-detector system in an airplane traveling at about 300 m (1,000 ft) AGL at approximately 82 m/s (160 knots) has been documented to be 13,000 Bq/m^2 (0.8 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.

Approximate Cost of Equipment: $10,000–$20,000 (rented), depending on such parameters as fuel costs, travel distance, etc.
Approximate Cost per Measurement: $1,000–$1,500 per km^2 surveyed

H.2.6 Dosimeters

System: Thermoluminescent Dosimeter
Field/Laboratory: Field and laboratory
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** Neutron, beta, x-ray

Applicability to Site Surveys: Thermoluminescence 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 onsite to determine the difference from background. Groups of TLDs should be posted for fixed time periods (i.e., duration of project, monthly, quarterly, semi-annually, etc.) in locations of interest and compared to background radiation TLDs to identify locations of increased onsite doses.

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 sensitivity 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 TLD to measure various types and energies of radiation.

Specificity/Sensitivity: TLDs are primarily sensitive to gamma radiation, but selected TLD/filter arrangements can be used to measure beta, x-ray, and neutron radiation. They are posted both onsite and offsite in comparable areas. These readings are compared to determine whether the site can cause personnel to receive more radiation exposure than would be received from background radiation. The low-end sensitivity 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.

Approximate Cost of Equipment: $5,000–$ 100,0000 (reader), $25–$40 (TLD); TLDs cost $5–$40 per rental

Approximate Cost per Measurement: $25–$125

System: Electronic Dosimeters
Field/Laboratory: Field and laboratory
Radiation Detected: ***Primary:*** Gamma ***Secondary:*** Neutron, beta, x-ray

Applicability to Site Surveys: Application of electronic dosimeters (EDs) to site surveys is similar to TLDs in that they 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 motion of its majority charge carriers (holes or electrons). The electrical contact of the anode (P-type region) and the cathode (N-type region) are 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 utilized for measuring deep-dose gamma radiation. However, there are types of ED 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. 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/radio frequency interference. However, high magnetic fluxes can also cause false dose readings.

Neutron EDs must be calibrated to the energy fields they will be used in, as they do not have a linear energy response curve; hence, a neutron dosimeter calibrated to plutonium-beryllium neutrons may not provide an accurate dose for dry cask storage neutrons.

Neutron dosimeter response depends on the energy and fluence of the neutrons being measures. Specific correction factors may be needed for different applications.

Approximate Cost of Equipment: $375 (ED), $800 (reader)
Approximate Cost per Measurement: $0.01–$1, depending upon the number of times the dosimeter is read over its lifetime

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 analysis based on optical—rather than thermal—stimulation to release charge carriers from trapping centers. However, application of OSL dosimeters to site surveys is similar to TLDs, in that they 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 (i.e., duration of project, monthly, quarterly, semi-annually, etc.) 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, and shielding studies, as well as determining exposure to members of the public.

Operation: OSL is the method of analysis applied to the dosimeter. OSL dosimeters are made up 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 ($^{6}Li_2CO_3$, 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.

The readers capable of reading the OSL dosimeters are both 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 using a computer interface. The field reader allows measurement on demand, and the OSL dosimeters can be sent to 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. The environmental dosimeter contains the open window, plastic and copper filters only. OSL dosimeter is of rectangular design 5 cm x 2.4 cm x 0.6 cm thick, constructed of polystyrene plastic. Two flexible black gaskets are applied to the case to prevent light entry under extreme outdoor conditions. The holder is of rectangular design, 6.3 cm x 4.5 cm x 0.6 cm thick, constructed of polyvinyl chloride plastic, radiofrequency sealed, and waterproof. 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 dosimeters during the posting period. If the OSL dosimeters are processed at an offsite location, the transit dose (e.g., dose incurred within the OSL 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 sensitivity 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. They are posted both onsite and offsite in comparable areas. These readings are compared to determine whether the site can cause personnel to receive more radiation exposure than would be received 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 a millirem ambient dose equivalent. Photons (x- and gamma rays) with energies above 15 keV can be measured in the range of 1 μSv to 10 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.

Approximate Cost of Equipment: $25–$40 (OSL dosimeter), $5,000–$100,000 (reader); OSL dosimeters cost $5–$40 per rental
Approximate Cost per Measurement: $25–$125

H.2.7 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. The measurement of radon flux can also be achieved 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. 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 absorbers are designed to measure radon concentrations in indoor air. Some charcoal absorbers are sensitive to drafts, 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 millibecquerels $(mBq)/m^3$ (Bq/liter [L]) (0.2–1.0 pCi/L).

Approximate Cost of Equipment: $10,000 (liquid scintillation counter), $10,000 (NaI multichannel analyzer system), or $30,000+ (germanium multichannel analyzer system); not applicable when provided by a vendor. The cost of the activated charcoal itself is minimal.
Approximate Cost per Measurement: $5–$30, including the cost of canister and analysis

System: Alpha Track Detector
Field/Laboratory: Field and laboratory
Radiation Detected: ***Primary:*** Alpha particles (radon gas) ***Secondary:*** Thoron

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 (^{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 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 (BqL^{-1}-day^{-1}). The sensitivity is a function of detector design and exposure duration and also a function of the size of the area being read by laboratory. It is on the order of 0.04 mBq/m^3-day (0.04 Bq/L-day; 1 pCi/L-day).

Approximate Cost of Equipment: Not applicable when provided by a vendor
Approximate Cost per Measurement: $5–$25

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 (at least once per hour) 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 principle of operation of monitors equipped with solid-state detectors is 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 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.

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. In locations where external power is unavailable, the available operating time depends on the battery lifetime of the monitor. The MDC for these detectors ranges from 0.004–0.04 mBq/m^3 (Bq/L; 0.1–1.0 pCi/L).

Approximate Cost of Equipment: $2,000–$7,000.
Approximate Cost per Measurement: $80+, based on duration of survey.

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 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. Ionization events within the chamber reduce the charge on the electret. The electret charge is measured with the voltage reader before and after deployment; the rate of change of the charge, with applied calibration or background compensation factors, is proportional to the radiation level or dose. 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. For radon measurements, radon diffuses through a filter into the ion chamber, where the ionization produced by the decay of radon and its progeny reduces the charge on the electret. 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-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 device to acclimate. It can be used in the field, but taking it 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. Due to their small size (3.8 cm tall x 7.6 cm in diameter), they may be deployed in hard-to-access locations.

Specificity/Sensitivity: Electrets are designed to make radon measurements 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 ranges for radon measurements ranges from 0.007–0.02 mBq/m^3 (Bq/L; 0.2–0.5 pCi/L).

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 ^{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 15–1200 keV, and fading corrections are not required. To quantify ambient gamma radiation fields of 10 μR/h, a 1,000 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.

Approximate Cost of Equipment: $4,000–$25,000
Approximate Cost per Measurement: $8–$25

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 an approximately 250 mm (10 in.)-diameter polyvinyl chloride end cap, spacer pads, a charcoal distribution grid, a retainer pad with screen, and a steel retainer spring. Between 170 and 200 grams of activated charcoal is 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. This data is 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 greater than 24 hours are not recommended due to atmospheric and surface moisture and temperature extremes which may saturate the charcoal or affect charcoal efficiency.

Approximate Cost of Equipment: $20–$100
Approximate Cost per Measurement: included in the cost of equipment

H.2.8 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: This equipment is still in the testing phase. Laser ablation-inductively coupled plasma-atomic emission spectrometry (LA-ICP-AES) and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) are techniques are used to nondestructively screen and characterize very small samples of soils and concrete *in situ* to determine the concentration of radioactive material. It is particularly suited to measuring the surface concentration of uranium and thorium. The unit can assess the concentrations at various depths when lower levels are exposed by some means. It has the advantage of not consuming surface material, providing real time response, reducing sampling and analysis time, and keeping personnel clear of the materials being sampled. The information developed can assist in identifying locations for excavation.

Operation: 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 inductively coupled plasma torch, and a video monitor.

Sampling probes have been developed and prototyped that will screen/characterize surface soils, concrete floors or pads, and subsurface soils. The sampling probes, both surface and subsurface, contain the laser (a 50-hertz [Hz] neodymium-doped yttrium aluminum garnet laser), associated optics, and control circuitry to raster the laser (ablation) energy across 1 $in.^2$ of sample surface. Either sampling probe is connected by an umbilical, currently 20 m long, to the Mobile Demonstration Laboratory for Environmental Screening Technologies (MDLEST), a completely self-contained mobile laboratory containing the instrumentation to immediately analyze the samples generated by the laser ablation.

A fiber optic cable delivers laser light to the surface of interest. This ablates a small quantity of material that is carried away in a stream of argon gas. The material enters the plasma torch where it is vaporized, atomized, ionized, and electrically excited at about 8,000 K. This produces an ionic emission spectrum that is analyzed on the atomic emission spectrometer.

The analysis instrumentation (i.e., ICP-AES/MS) in the MDLEST does not depend on radioactive decay for detection but looks directly at the atomic makeup of the elements(s) of interest. A large number of metals, including the longer half-life radioactive elements, can be detected and quantified. The spectrometer is set up using either hardware, software, or both to simultaneously detect all elements of interest in each sample.

The MDLEST can be set up onsite to monitor soil treatment processes. This function enables 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 is attained.

Specificity/Sensitivity: This system measures the surface or depth concentration of atomic species and is particularly suited to uranium and thorium analysis. It is 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 LA-ICP-MS taking about 30 minutes. The detection limits for the two spectrometers that have been used are as follow:

1. The LA-ICP-AES can see ppm levels for some 70 elements and reportedly detects uranium and thorium concentrations at 1 ppm, or 10 Bq/kg (0.3 pCi/g) for ^{238}U and 0.4 Bq/kg (0.1 pCi/g) for ^{232}Th. However, the technique is only sensitive to elements; it cannot discriminate between the different isotopes of uranium and thorium. This prevents it from being used for assessing lower atomic number elements that have stable isotopes or from determining relative abundances of isotopes of any element. This may significantly limit its use at some sites.

2. The LA-ICP-MS can see sub–parts per billion (ppb) levels and is capable of quantifying the uranium and thorium isotopes. This system has been used to search for ^{230}Th and ^{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 concentration of soil more sensitively than the LA-ICP-AES system.

Approximate Cost of Equipment: > $1,000,000.
Approximate Cost per Measurement: $4,000 (LA-ICP-AES), unavailable (LA-ICP-MS)

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, etc. 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 lab 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 supply, amplifier, analog-to-digital converter, multichannel analyzer, and computer. The bias is typically 25–100 V. The vacuum is typically less than 10 micrometers of Hg (0 ° Celsius [C]). 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 a breakdown of the diode 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 lab, where they are placed in solution and the element of interest (uranium, plutonium, *etc.*) 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 can be resolved by the system. 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.

Approximate Cost of Equipment: $10,000–$100,000, based on the number of detectors and sophistication of the computer and data reduction software; this does not include the cost of equipment for the chemistry lab.

Approximate Cost per Measurement: $250–$400 for the first element, $100–$200 for each additional element per sample, $200–$300 additional for a rush analysis; the additional element cost depends on the separation chemistry involved and may not always be less.

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 if 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 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 < 2%/100 V and be > 800 V long. The beta plateau should have a slope of < 2.5%/100 V and be > 200 V long. Operation on the beta plateau will also allow detection of some gamma radiation and bremsstrahlung (a type of x-rays), 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 < 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, < 0.2 cpm (< 0.04 cpm guarded), depending on detector size. Typical (4-π) efficiencies for very thin alpha sources are 35–45 percent (window) or 40–50 percent (windowless). 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 4-π efficiency for a thin ^{90}Sr/^{90}Y source is > 50 percent (window) to > 60 percent (windowless) but can reduce to < 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.

Approximate Cost of Equipment: \$4,000–\$5,000 (manual), \$25,000–\$30,000 (automatic)
Approximate Cost per Measurement: \$30–\$50, plus radiochemistry

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 50 mm (2 in.)-diameter silicon detector, a small vacuum chamber, a roughing pump, a multichannel analyzer, 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 ^{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 min 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.

Approximate Cost of Equipment: $11,000
Approximate Cost per Measurement: $25–$100

H.3.2 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 if 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 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 their 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 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 < 2%/100 V and be > 800 V long. The beta plateau should have a slope of < 2.5%/100 V and be > 200 V long. Operation on the beta plateau will also allow detection of some gamma radiation and bremsstrahlung (x-rays), but the efficiency is very low. Crosstalk between the alpha-to-beta channels is typically about 10 percent, whereas beta-to-alpha channels should be < 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, < 0.2 cpm (< 0.04 cpm guarded), depending on detector size. Typical (4-π) efficiencies for very thin alpha sources are 35–45 percent (window) and 40–50 percent (windowless). 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 4-π efficiency for a thin ^{90}Sr/^{90}Y source is > 50 percent (window) to > 60 percent (windowless) but can reduce to < 5 percent for a thick source. Minimum detectable activities for guarded gas-flow proportional counters are usually lower than for internal proportional counters because of the lower backgrounds.

Approximate Cost of Equipment: \$4,000–\$5,000 (manual), \$25,000–\$30,000 (automatic)
Approximate Cost per Measurement: \$30–\$50 plus radiochemistry

System: Liquid Scintillation Spectrometer
Field/Laboratory: Laboratory (primary), field (secondary)
Radiation Detected: ***Primary:*** Beta ***Secondary:*** Alpha, 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 ^{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 photomultiplier tubes (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 multi-energy 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 has 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.

Approximate Cost of Equipment: $20,000–$70,000, based on the specific system features
Approximate Cost per Measurement: $50–200, plus cost of chemical separation, if required

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, air filters, etc., with little preparation. NaI is inherently more efficient for detecting gamma rays but has lower resolution than germanium, particularly 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 a multichannel analyzer. The detector is an NaI crystal connected to a photomultiplier tube (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 multichannel analyzer 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 sensitivity. 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 cost is approximately $100,000 each, compared with $3,000 for a NaI detector. NaI measures energies over 80 keV. The instrument response is energy dependent, the resolution is not superb, and the energy calibration is not totally linear, so care should be taken when identifying or quantifying multiple isotopes. Computer software can help interpret complicated spectra. NaI is fragile and should be protected from shock and sudden temperature changes.

Approximate Cost of Equipment: $6,000–$20,000
Approximate Cost per Measurement: $100–$200 per sample.

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, air filters, etc. 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 a multichannel analyzer. P-type germanium detectors typically operate from +2000 to +5000 V; N-type germanium detectors operate from -2000 to -5000 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 use 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 beryllium-end window is good for 5–80 keV energies using a thinner sample placed over the window.

Approximate Cost of Equipment: $35,000–$150,000, based on detector efficiency and sophistication of MCA/computer/software system
Approximate Cost per Measurement: $100–$200; rush requests can double or triple costs

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. It 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 M/R. 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 M/R 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.

There are different types of mass spectrometric systems and techniques that can be employed for radiological applications. For example, isotope ratio mass spectrometers (IR-MS) 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 inductively coupled plasma (ICP) mass spectrometer (ICP-MS) units are commercially available, including single- and multicollector magnetic-sector ICP-MS and quadrupole ICP-MS. These benchtop units are commercially available at a reasonable price. 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 much of the periodic table elements, (2) an analytical working range of nine 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 radio frequency 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 MS 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 one 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 guides the desired ions into the quadrupole while assuring 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 mass spectroscopy 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, ^{129}I, ^{237}Np)—ICP-MS may be faster and more sensitive than nuclear-decay emission analyses. 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 *vs.* ^{235}U and ^{239}Pu *vs.* ^{240}Pu). This information is frequently useful in determining the age or origin of materials (ASTM C758, C759, and C799). Typically, ICP-MS are 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 and, therefore, should have 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 ^{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.

Approximate Cost of Equipment: > $1,000,000.
Approximate Cost per Measurement: Not available

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: Thermal ionizing mass spectrometry (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. Similar to the standard mass spectrometry technique, 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 mass spectrometric 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 (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 (microbecquerels [µBq]/L). TIMS has also been used to evaluate the isotopic ratio of $^{238}U/^{235}U$ in urine samples. Various mass spectrometers were used, including sector-field ICP-MS, quadrupole ICP-MS, and TIMS. The TIMS and quadrupole ICP-MS had similar detection limits: 0.1 picograms (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 between 138:1–220:1 for three test levels of 25–100 nanograms [ng]/kg, 100–350 ng/kg, and greater than 350 ng/kg. For more details see Multi-Agency Radiation Laboratory Analytical Protocols, NRC 2004.

Approximate Cost of Equipment: Not available
Approximate Cost per Measurement: Not available

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 mass spectrometric analysis. A special merit of AMS among other mass spectrometric methods is its power to separate a rare isotope from an abundant neighboring mass ("abundance sensitivity"; e.g., ^{14}C from ^{12}C). The method suppresses molecular isobars completely and, in many cases, can separate atomic isobars (e.g., ^{14}N from ^{14}C). Thus, it makes possible for AMS to 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 can outperform the competing technique of decay counting for all isotopes where the half-life is long enough.

Operation: AMS techniques involve the acceleration of ions to extraordinarily high kinetic energy before mass spectrometric analysis. The AMS system is technically sophisticated, expensive, and fairly large, and requires extensive laboratory space and facilities. In 2012, in nine North American organizations had AMS systems (primarily for earth science, radiometric dating, bioscience and environmental studies applications). The organizations include the Woods Hole Oceanographic Institution; the University of Ottawa; Purdue University; the University of Arizona; the University of Florida, Miami; the University of California, Los Angles; the University of California, Irvine; the Naval Research Lab, Washington, DC; and the Lawrence Livermore National Laboratory (LLNL). 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, ^{32}Si, ^{36}Cl and ^{41}Ca. In addition, ^{63}Ni, ^{129}I, and $^{239/240}$ Pu are routinely analyzed by AMS at LLNL. **Table H.1** (McAninch, 1999) provides the detection limits for these radionuclides (for more details, see also NRC 2004, Chapter 15).

Table H.1: Accelerator Mass Spectrometry Detection Limits

Nuclide	Detection Limit (nBq)	Detection Limit (105 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

Abbreviation: nBq = nanobecquerels.

Approximate Cost of Equipment: Not available
Approximate Cost per Measurement: Not available

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 spectrometer (FA-MS) is used for the determination of H 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. The flowing-afterglow technique can be used to identify and quantify the volatile organic compounds (VOCs) 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 employed to unequivocally identify the VOCs include using 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 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 He^+ or Ar^+ ions reacting with trace amounts of 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 ^{1}H and ^{2}H.) 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 ^{2}H, ^{17}O and ^{18}O isotopic variants. The mixture of ions is sampled from the flowing swarm via a pinhole orifice located at the downstream end of the flow tube, and they 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 parts per billion range, if there is limited sample, or parts per trillion, if there is an unlimited sample size.

Approximate Cost of Equipment: Not available
Approximate Cost per Measurement: Not available

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 vacuum using electrical fields, it is necessary to ionize or induce charge on them. Charging of the molecules can be achieved by bombarding 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; forensic 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, all the air molecules have to be pumped out to create an ultra-high vacuum. In the typical vacuum inside a TOF-MS, an ion can fly on average 600 m (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. Charging of the molecules can be achieved 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 is dependent upon their mass, measuring the flight 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 upon 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.

Approximate Cost of Equipment: Not available
Approximate Cost per Measurement: Not available

System: Chemical Speciation Laser Ablation Mass Spectrometer
Field/Laboratory: Field
Radiation Detected: None

Applicability to Site Surveys: Chemical species laser ablation mass spectrometry 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 mass spectrometry. 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 in the development of compact portable laser ablation mass spectrometry instrumentation for field-based analyses.

Specificity/Sensitivity: This system can analyze soils and surfaces for organic and inorganic molecular species, with excellent sensitivity. Environmental concentrations in the range of 10^{-9}–10^{-14} g/g can be determined, depending on environmental conditions. It is highly effective when used by a skilled operator, but it is of limited use due to 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.

Approximate Cost of Equipment: Very expensive (prototype)
Approximate Cost per Measurement: May be comparable to LA-ICP-AES and LA-ICP-MS. When using the atomic emission spectrometer, the reported cost is $4,000 per sample, or 80 percent of conventional sampling and analysis costs. This high cost for conventional samples is partly due to the 2- or 3-day time to analyze certain radionuclides by conventional methods. When using the mass spectrometer, the time required is about 30 minutes per sample.

H.3.5 Specialized Analysis

System: Kinetic Phosphorescence Analysis by Laser
Field/Laboratory: Laboratory (primary), Field (secondary)
Radiation Detected: Uranium or Lanthanum

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. 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. 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. There are several types of interferences that should be considered. The interferences can be differentiated into five categories: (1) light absorption agents, such as yellow solutions and ferric iron; (2) lumiphors, such as oils and humic acid; (3) quenching agents, including alcohols, halides (except fluoride), and certain metals; (4) competing reactions; and (5) HCl. 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 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 ASTM D5174 method, 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 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.

Approximate Cost of Equipment: Not available

Approximate Cost per Measurement: Not available

System: Instrumental Neutron Activation Analysis
Field/Laboratory: Field and 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—

- 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 via 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 in the order of 10^{12}–10^{14} neutrons cm^{-2} s^{-1}, depending on the reactor power. In general, a 1 MW 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 volts. 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 via 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 photon. This decay process is at a much slower rate than the initial de-excitation and is dependent on unique half-life of the radioactive nucleus. These unique half-lives are dependent upon 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 Cf, which emits neutrons through spontaneous fission; an alpha source, such as Ra or Am mixed with Be, which generates neutrons by a (α,^{12}C+n) reaction; and a D-T fusion reaction in a gas discharge tube. There are different detector types and configurations 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 type, scintillation type, and semiconductor type. Of these, the scintillation and semiconductor type 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 labs. A second disadvantage of INAA is the time required for the counting which could be for several days or more to achieve the required detection limits.

Specificity/Sensitivity: INAA can detect up to 74 elements depending upon the experimental procedure, with minimum detection limits in the range of 0.1– 1.0 x 10^6 ng/g depending on element of concern.

Approximate Cost of Equipment: Not available
Approximate Cost per Measurement: Not available

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	Approximate Equipment Cost	Approximate Measurement Cost
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 sensitivity is 10 cpm (1 cpm with headphones).	$2,000–$4,000	$10
Gas-flow proportional counter (field)	A detector through which P-10 gas flows and which that measures alpha and beta radiation.; < 1-–10 mg/cm^2 window, probe face area 50 to –100 cm^2 for hand -held detectors; , up to 600 cm^2 if cart mounted	Surface scanning, surface activity measurement, or field evaluation of swipes. S; serves as a screen to determine if more nuclide-specific analyses are needed.	Natural radionuclides in samples can interfere with the detection of other radionuclides. The instrument, equires P--10 gas.	$2,000-–$5,000	$5-–$15/m^2

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
Alpha spectroscopy with Multi-Channel 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.	\$10,000–\$100,000	\$250–\$400 for the first element, \$100–\$200 for each additional element per sample, \$200–\$300 additional for a rush analysis
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.	\$4,000–\$5,000 (manual) and \$25,000–\$30,000 (automatic)	\$30–\$50, plus radiochemistry
Liquid scintillation counter (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	Highly selective for alpha or beta radiation by pulse shape discrimination. Requires LSC cocktail.	\$20,000–\$70,000	\$50–\$200

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
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	$11,000	$25-$100

Abbreviations: mg = milligram; cm = centimeter; cpm = counts per minute; m = meter; LSC = liquid scintillation counter.

Table H.3: Radiation Detectors with Applications to Beta Surveys

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
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 will distinguish between both alpha and beta radiations in a mixed field.	$2,000–$4,000	$10
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	Surface scanning, surface activity measurement, or field evaluation of swipes; a screen to determine if 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.	$2,000–$5,000	$2–$15/m^2

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
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.	\$800–\$2,000	\$5–\$10
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.	\$4,000–\$5,000 (manual) and \$25,000–\$30,000 (automatic)	\$30 - \$50, plus radiochemistry
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 isighly selective for alpha and beta radiation by pulse shape discrimination	\$20,000–\$70,000	\$50–\$250

Abbreviations: in. = inch; mg = milligram; cm = centimeter; FSS = final status survey; LSC = liquid scintillation counter.

Table H.4: Radiation Detectors with Applications to Gamma and X-Ray Surveys

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
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.	$1,000–$1,500	$5
Hand-held pressurized ion chamber survey meter (field)	Ion chamber for measuring higher radiation levels than typical background	Measuring true gamma exposure rate with more sensitivity than the unpressurized ion chamber	The meter is not very useful for site surveys because of high detection limit above background levels.	$1,000–$1,500	$5
Pressurized ionization chamber (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.	$15,000–$50,000	$50–$500
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.	$800–$2,000	$10

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
Sodium iodide survey meter (field)	Detector sizes up to ~200 mm x 200 mm (8 in. x 8 in); used in micro-R meter in smaller sizes	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 pressurized ion chamber for a specific site.	$2,000	$5
Lanthanum bromide survey meter (field)	Comparable scintillation crystal thicknesses to sodium iodide 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 sodium iodide survey meters.	$10,000–$45,000	$10–$50
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.	$10,000–$60,000	$10–$60
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.	$40,000–$80,000	$100–$300

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
FIDLER probe with survey meter (field)	Thin crystals of NaI or CsI	Scanning of gamma/x-radiation from plutonium and americium	FIDLER probes are most useful for determining the presence of Pu 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 Pu is present.	$4,000–$7,000	$10–$20
Field x-ray fluorescence spectrometer (field)	Uses silicon or germanium semiconductor	Determining fractional abundance of low percentage metal atoms	—	$15,000–$75,000	$200
Sodium iodide detector with multichannel analyzer (laboratory)	Sodium iodide crystal with a large range of sizes and shapes, connected to a photomultiplier tube and multichannel analyzer	Field or 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.	$6,000–$20,000	$100–$200

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
Germanium detector with multichannel analyzer (laboratory)	Intrinsic germanium semiconductor in p- or n-type configuration and without a beryllium window	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.	\$35,000–\$150,000	\$100–\$200
Thermoluminescence dosimeter (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.	\$5,000–\$100,000 for reader	\$25–\$125 per TLD
Electronic dosimeter (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 utilized 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 1000 rem exposure and have an energy response from 60 keV to 6 MeV.	\$375 (ED), \$800 (reader)	\$0.01–\$1.00

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
Optically stimulated luminescence dosimeter (field and laboratory)	Non-destructive 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.	\$5,000–\$100,000 (reader), \$25–\$40 (OSL dosimeter), \$5–\$40 (OSL dosimeter rental)	\$25–\$125

Abbreviations: mg = milligram; cm = centimeter; mR = milliroentgen; h = hour; mm = millimeter; in. = inch; keV = kiloelectron volt; s = second; FSS = final status survey; FIDLER = field instrument for the detection of low-energy radiation; TLD = thermoluminescence dosimeter; ED = electronic dosimeter; mrem = millirem; OSL = opitcally stimulated luminescence; OSLN = OSL devices sensitive to neutrons.

Table H.5: Radiation Detectors with Applications to Large Area Mobile Detector Arrays

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
Aerial systems (field)	Array of high-efficiency detectors mounted on an airplane or helicopter that performs low-level flights	Surveying very large areas to detect gamma and neutron 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.	\$10,000–\$20,000 (rented)	\$1,000–\$1,500 per km^2 surveyed

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
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 sodium iodide detector 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.	\$10,000–\$100,000	\$70,000 per km^2 surveyed

Abbreviations: mm = millimeter; in. = inch; FIDLER = field instrument for the detection of low-energy radiation.

Table H.6: Radiation Detectors with Applications to Radon Surveys

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
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 LLD is 0.007–0.04 mBq/m^3 (Bq/L; 0.2–1.0 pCi/L).	\$10,000–\$30,000	\$5–\$30, including canister, if outsourced
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	LLD is 0.04 mBq $m^{-3}d^{-1}$ (Bq L^{-1} d^{-1}; 1 pCi $L^{-1}d^{-1}$).	Not applicable when provided by a vendor	\$5–\$25

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
Continuous/ integrating radon monitor (field)	Air pump and scintillation cell or ionization chamber	Tracking the real-time concentration of radon	Takes 1–4 hours for system to equilibrate before starting. The LLD is 0.004–0.04 mBq/m^3 (Bq/L; 0.1–1.0 pCi/L).	\$2,000–\$7,000	\$80
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. LLD is 0.007–0.02 mBq/m^3 (Bq/L) (0.2–0.5 pCi/L).	\$4,000–\$25,000	\$8–\$25 for rental
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	The LLD is 0.007 Bq m^{-2}s^{-1} (0.2 pCi m^{-2}s^{-1}).	Not applicable (rented)	\$20–\$50, Including canister

Abbreviations: LLD = lower level of detection; mBq = millibecquerel; m = meter; Bq = becquerel; L = liter; pCi = picocurie; d = day.

Table H.7: Systems that Measure Atomic Mass or Emissions

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
Laser ablation-inductively coupled plasma-atomic emission spectrometry (field)	Vaporizes and ionizes the surface material and measures emissions from the resulting atoms	Live analysis of radioactive U and Th concentrations in the field	The spectrometer requires expensive equipment and skilled operators. LLD is 0.004 Bq/g (0.1 pCi/g) for ^{232}Th and 0.01 Bq/g (0.3 pCi/g) for ^{238}U.	>$1,000,000	$4,000
Laser ablation-inductively coupled plasma-mass spectrometry (field)	Vaporizes and ionizes the surface material, then measures the mass of the resulting atoms	Live analysis of radioactive U and Th 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.	>$1,000,000	Unavailable
Chemical speciation laser ablation/mass spectrometer (field)	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.	>$1,000,000	>$4,000
Thermal ionizing mass spectrometry (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 mass spectrometry technique, TIMS is frequently used to determine isotopic composition and measurement of isotopes at low concentrations in water and soil.	Not Available	Not Available

System	Description	Application	Remarks	Approximate Equipment Cost	Approximate Measurement Cost
Accelerator mass spectrometry (laboratory)	Direct detection of isotopes based on mass to charge ratio	Determination of hydrogen isotopes in water and liquid environmental samples	AMS differs from other mass spectrometry techniques in that it depends on acceleration of ions to extraordinarily high kinetic energy before mass spectrometric analysis.	Not Available	Not Available
Flowing afterglow mass spectrometer (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 mass spectrometry analytical technique that offers online, real-time ^{2}H abundance measurements in water vapor above aqueous liquids, including urine and serum.	Not Available	Not Available
Time-of-flight mass spectrometry (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	—	Not Available	Not Available

Abbreviations: LA-ICP-AES = laser ablation-inductively coupled plasma-atomic emission spectrometer; LLD = lower level of detection; Bq = becquerel; g = gram; pCi = picocurie; TIMS = thermal ionizing mass spectrometry; AMS = accelerator mass spectrometry; FA-MS = flowing afterglow mass spectrometry; ppt = parts per trillion; TOF-MS = time-of-flight mass spectrometry.

Table H.8: Special Techniques and Equipment

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
Instrumental neutron activation analysis (field and 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 (0.1–1.0) x10^6 ng. g^{-1} depending on element of concern.	Not Available	Not Available
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%.	Not Available	Not Available

Abbreviations: INAA = instrumental neutron activation analysis; ng = nanograms; ppb = parts per billion.

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

Negative values of z can be obtained from the relationship: $\Phi(-z) = 1 - \Phi(z)$.

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

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
3.5	18	16	13	11	8	13	11	9	6	9	8	5	6	4	2
4.0	18	15	13	11	8	13	11	9	6	9	7	5	6	4	2

1 ## I.3 Critical Values for the Sign Test

2 **Table I.4: Critical Values for the Sign Test Statistic S+**

N	Alpha (α)								
	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

N	Alpha (α)								
	0.005	***0.01***	***0.025***	***0.05***	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***
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
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:**

$$S+=\frac{N}{2}+\frac{z}{s}\sqrt{N} \quad \text{(I-1)}$$

where z is the $(1-\alpha)$ percentile of a standard normal distribution, which can be found on page I-11 or in **Table O.2.**

I.4 Critical Values for the WRS Test

Table I.5: Critical Values for the WRS 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
$\alpha = 0.1$	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
$\alpha = 0.001$	207	224	239	254	268	282	296	309	323	336	349	362	376	389	402	415	428	441	454
$\alpha = 0.005$	207	222	236	249	262	275	288	301	313	326	339	351	364	376	388	401	413	425	438
$\alpha = 0.01$	206	220	233	246	259	272	284	296	309	321	333	345	357	370	382	394	406	418	430
$\alpha = 0.025$	204	217	230	242	254	266	278	290	302	313	325	337	348	360	372	383	395	406	418
$\alpha = 0.05$	202	215	226	238	250	261	273	284	295	307	318	329	340	352	363	374	385	396	407
$\alpha = 0.1$	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
$\alpha = 0.001$	228	246	262	277	292	307	321	335	350	364	377	391	405	419	433	446	460	473	487
$\alpha = 0.005$	227	243	258	272	286	300	313	327	340	353	366	379	392	405	419	431	444	457	470
$\alpha = 0.01$	226	242	256	269	283	296	309	322	335	348	361	373	386	399	411	424	437	449	462
$\alpha = 0.025$	225	239	252	265	278	290	303	315	327	340	352	364	377	389	401	413	425	437	450
$\alpha = 0.05$	223	236	248	261	273	285	297	309	321	333	345	356	368	380	392	403	415	427	439
$\alpha = 0.1$	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
$\alpha = 0.001$	250	269	286	302	317	333	348	363	377	392	407	421	435	450	464	479	493	507	521
$\alpha = 0.005$	249	266	281	296	311	325	339	353	367	381	395	409	422	436	450	463	477	490	504
$\alpha = 0.01$	248	264	279	293	307	321	335	349	362	376	389	402	416	429	442	456	469	482	495
$\alpha = 0.025$	247	261	275	289	302	315	329	341	354	367	380	393	406	419	431	444	457	470	482
$\alpha = 0.05$	245	258	271	284	297	310	322	335	347	360	372	385	397	409	422	434	446	459	471
$\alpha = 0.1$	242	254	267	279	291	303	315	327	339	351	363	375	387	399	410	422	434	446	458

Reject the null hypothesis if the test statistic (W_r) is greater than the table (critical) value. For n or m greater than 20, the table (critical) value can be calculated from **Equation I-2:**

$$W_r = \frac{m(n+m+1)}{2} + z\sqrt{\frac{nm(n+m+1)}{12}} \qquad \text{(I-2)}$$

if there are few or no ties, and from **Equation I-3:**

$$W_r = \frac{m(n+m+1)}{2} + z\sqrt{\frac{nm}{12}\left[(n+m+1) - \sum_{j=1}^{g}\frac{t_j(t_j^2-1)}{(n+m)(n+m-1)}\right]} \qquad \text{(I-3)}$$

if there are many ties, where g is the number of groups of tied measurements and t_j is the number of tied measurements in the j^{th} group. z is the $(1-\alpha)$ percentile of a standard normal distribution, which can be found in **Table I.6** below:

Table I.6. Percentile of a Standard Normal Distribution

α	z
0.001	3.09
0.005	2.575
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.5 Probability of Detecting an Elevated Area

Guidance for using **Table I.7** can be found in Gilbert 1987 and EPA 1989b.

Table I.7: 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

L/G	Shape Parameter, S																			
	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%

L/G	Shape Parameter, S																			
	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
0.18	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%
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%

L/G	Shape Parameter, S																			
	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
0.41	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%
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%

L/G	Shape Parameter, S																			
	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
0.65	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%
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%

L/G	Shape Parameter, S																			
	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
0.89	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%
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.6 Test Statistics for the Quantile Test

Table I.8: 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

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**
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
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

Table I.9: 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

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**
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
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

Table I.10: 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

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		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
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

Table I.11: 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

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	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
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

I.7 Random Numbers

Table I.12: 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

Random Numbers Uniformly Distributed between Zero and One*									
0.536855	0.667083	0.636883	0.043774	0.113509	0.980045	0.237797	0.618925	0.670767	0.814902
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

*Note: To ensure random number generation using a table, ask a disinterested party to determine the random numbers off the table.

J DERIVATION OF ALPHA SCANNING EQUATIONS PRESENTED IN SECTION 6.3.2.2

For alpha survey instrumentation with a background of approximately one to three 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.

Discussion

Experiments yielding numerical values for a random variable x, where x represents the number of events occurring during a given time interval or 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

$$P(x;\ \lambda t) = \frac{e^{-\lambda t}(\lambda t)^x}{x!}, x = 0, 1, 2, \cdots \qquad \text{(J-2)}$$

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:

$$P(n; m) = \frac{e^{-m} m^n}{n!} \qquad \text{(J-3)}$$

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:

$$P(n; m) = \frac{e^{\frac{-GEd}{60v}}\left[\frac{GEd}{60v}\right]^n}{n!} = \frac{e^{\frac{-GEt}{60}}\left[\frac{GEt}{60}\right]^n}{n!} \qquad \text{(J-4)}$$

where:

G = source activity (decays per minute [dpm])

E = detector efficiency (4π)
d = width of the detector in the direction of scan (centimeters [cm])
v = scan speed (centimeters/second [cm/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:

$$P(n \geq 1) = 1 - P(n = 0) \qquad \text{(J-5)}$$

If it also is assumed that a single count is sufficient to cause a surveyor to stop and investigate further, then:

$$P(n \geq 1) = 1 - P(n = 0) = 1 - e^{\frac{-GEt}{60}} \qquad \text{(J-6)}$$

Figures J.1–J.3 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 a sufficient period of time such that if the residual radioactive material corresponding 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 by substituting the following parameters into **Equation J-5** and solving for $P(\geq 1) = 0.9$, giving:

$$G = CA/100 \qquad \text{(J-7)}$$

where:

C = derived concentration guideline level (dpm/cm^2)
A = detector area (cm^2)

[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.

Giving:

$$t = \frac{13{,}800}{CAE} \tag{J-8}$$

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 a sufficiently long period 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 stopping for further investigation. Assuming this to be a valid assumption, **Equation J-3** can be solved for $n \geq 2$ as follows:

$$\begin{aligned} P(n \geq 2) &= 1 - P(n=0) - P(n=1) \\ &= 1 - e^{\frac{-(GE+B)t}{60}} - \frac{(GE+B)t}{60} e^{\frac{-(GE+B)t}{60}} \\ &= 1 - e^{\frac{-(GE+B)t}{60}} \left(1 + \frac{(GE+B)t}{60}\right) \end{aligned} \tag{J-9}$$

where:

$P(n \geq 2)$ = probability of getting 2 or more counts during the time interval t
$P(n = 1)$ = probability of getting 1 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 [cpm])

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. The same assumptions were made when calculating these curves as were made for **Figures J.1–J.3** except that the background was assumed to be seven counts per minute.

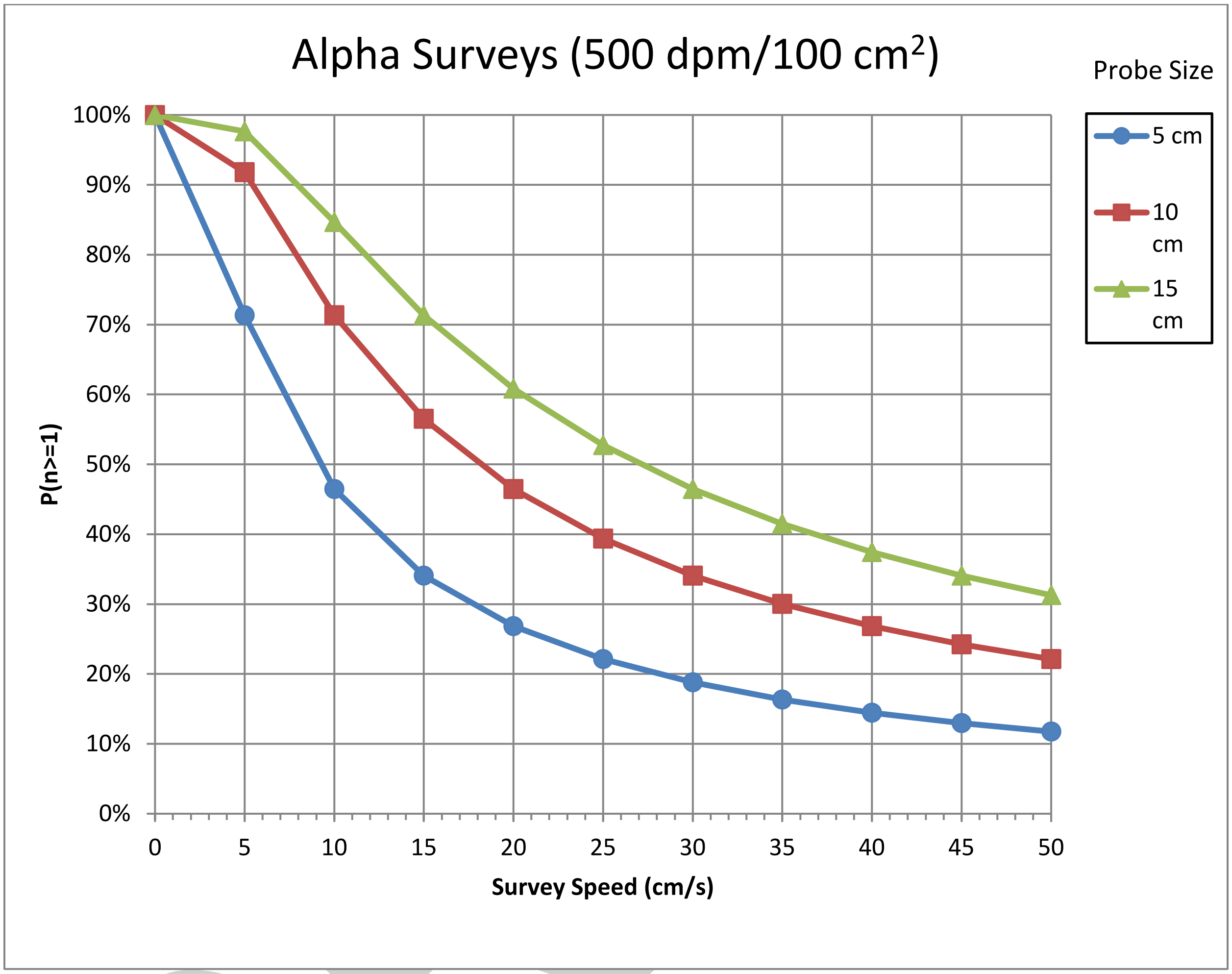


Figure J.1: Probability (P) of Getting One or More Counts When Passing Over a 100 cm^2 Area Containing Residual Radioactive Material at 500 dpm/100 cm^2 Alpha

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.

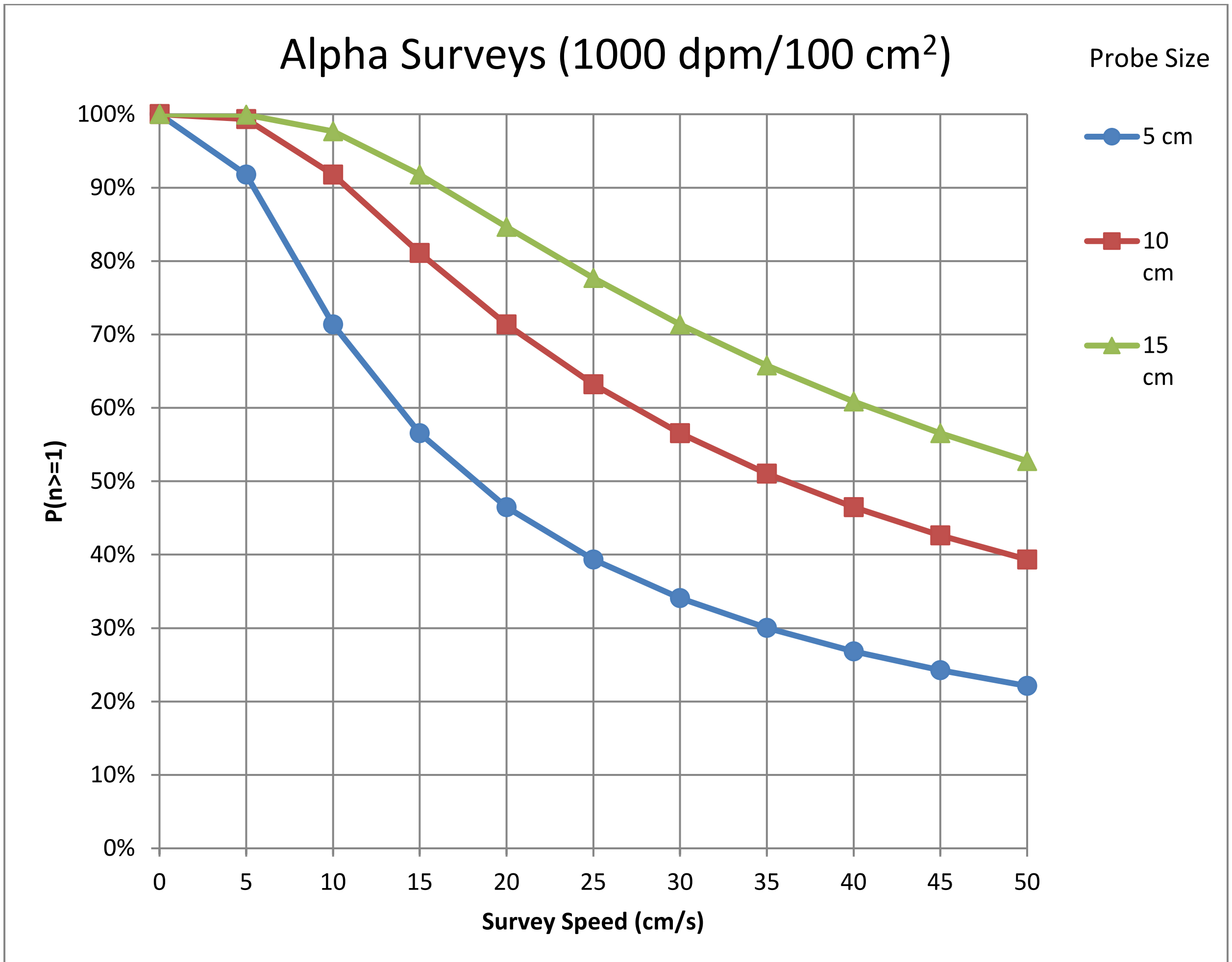


Figure J.2: Probability (P) of Getting One or More Counts When Passing Over a 100 cm^2 Area Containing Residual Radioactive Material at 1,000 dpm/100 cm^2 Alpha

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.

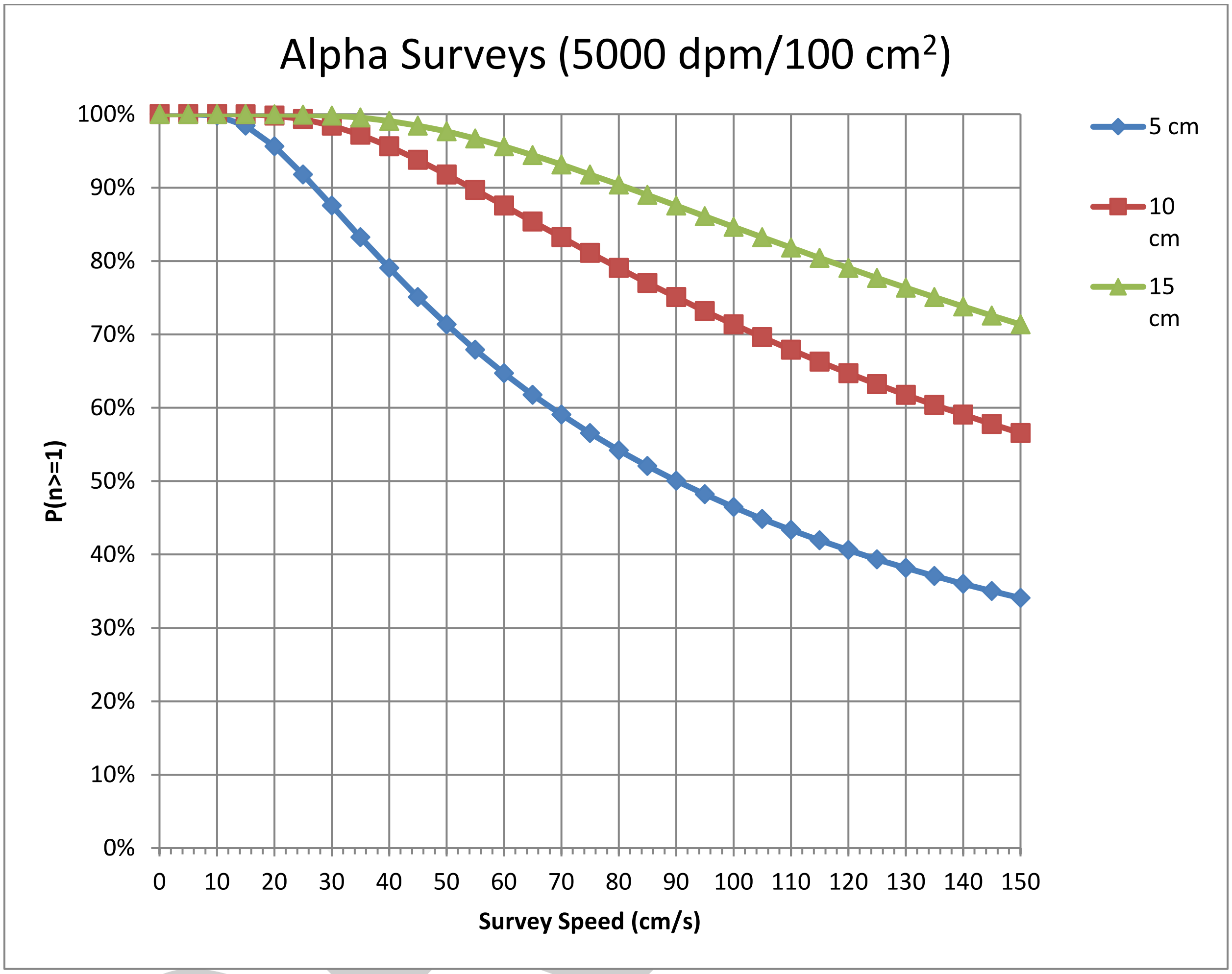


Figure J.3: Probability (P) of Getting One or More Counts When Passing Over a 100 cm^2 Area Containing Residual Radioactive Material at 5,000 dpm/100 cm^2 Alpha

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.

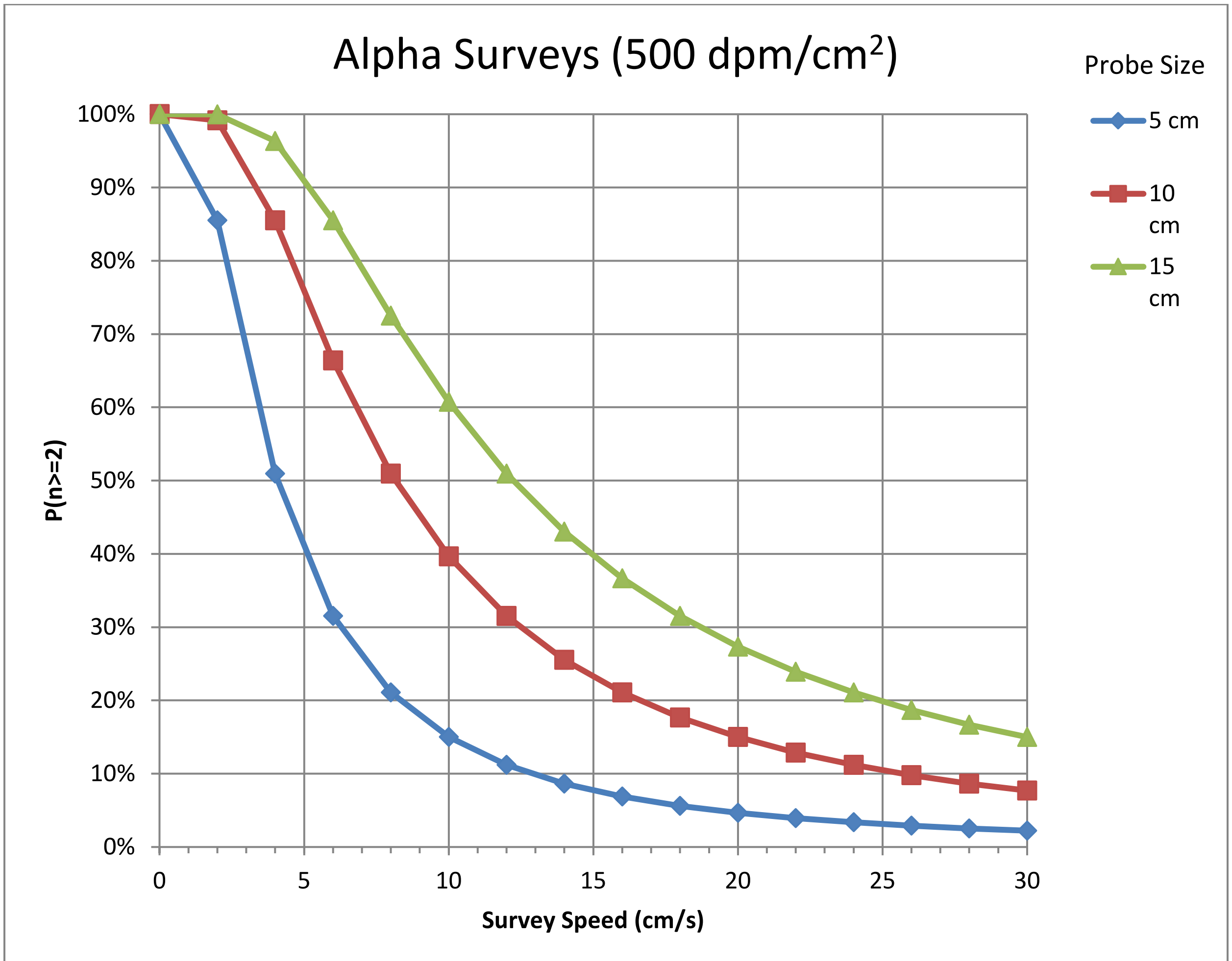


Figure J.4: Probability (P) of Getting Two or More Counts When Passing Over a 100 cm^2 Area Containing Residual Radioactive Material at 500 dpm/100 cm^2 Alpha

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.

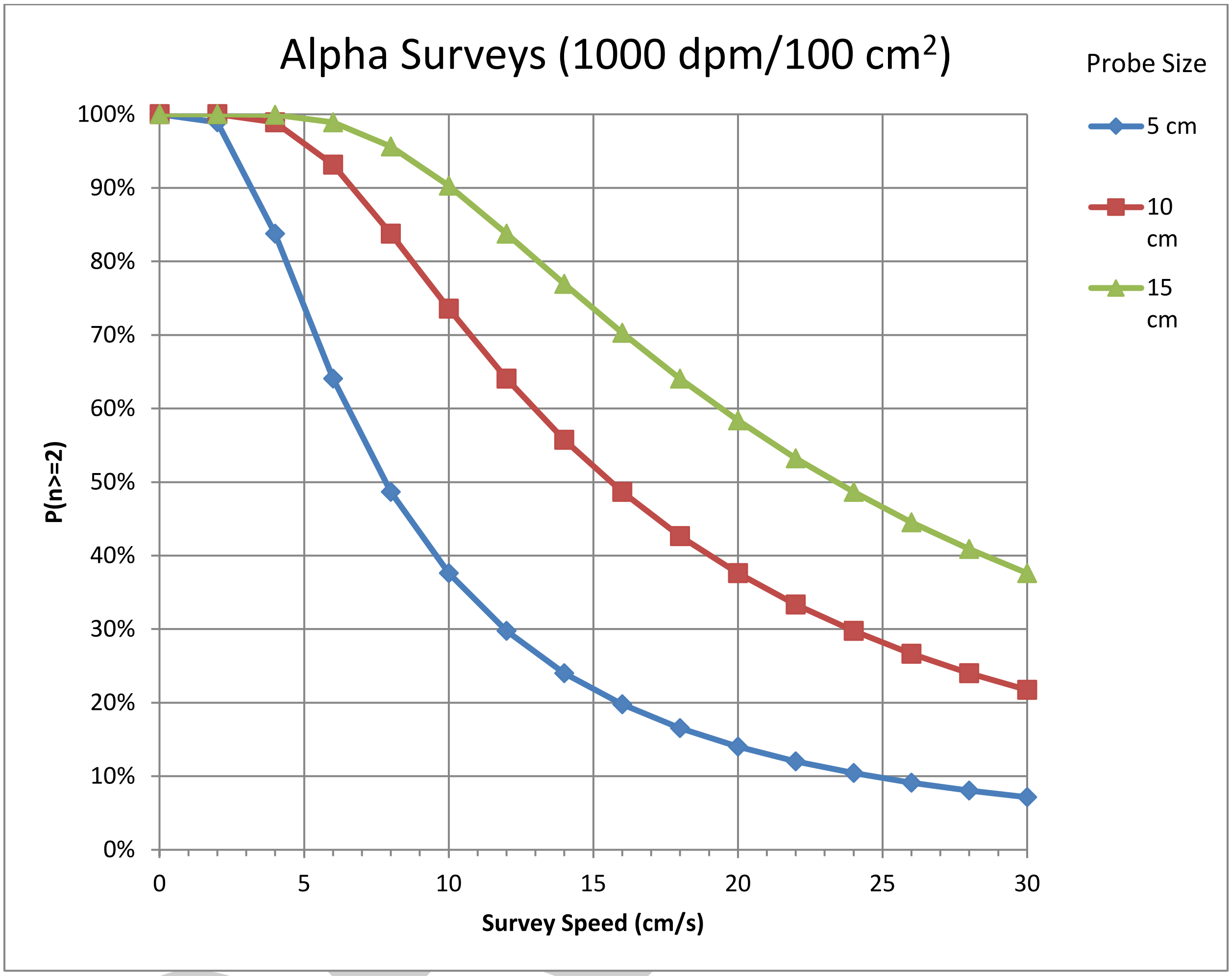


Figure J.5: Probability (P) of Getting Two or More Counts When Passing Over a 100 cm² Area Containing Residual Radioactive Material at 1,000 dpm/100 cm² Alpha

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.

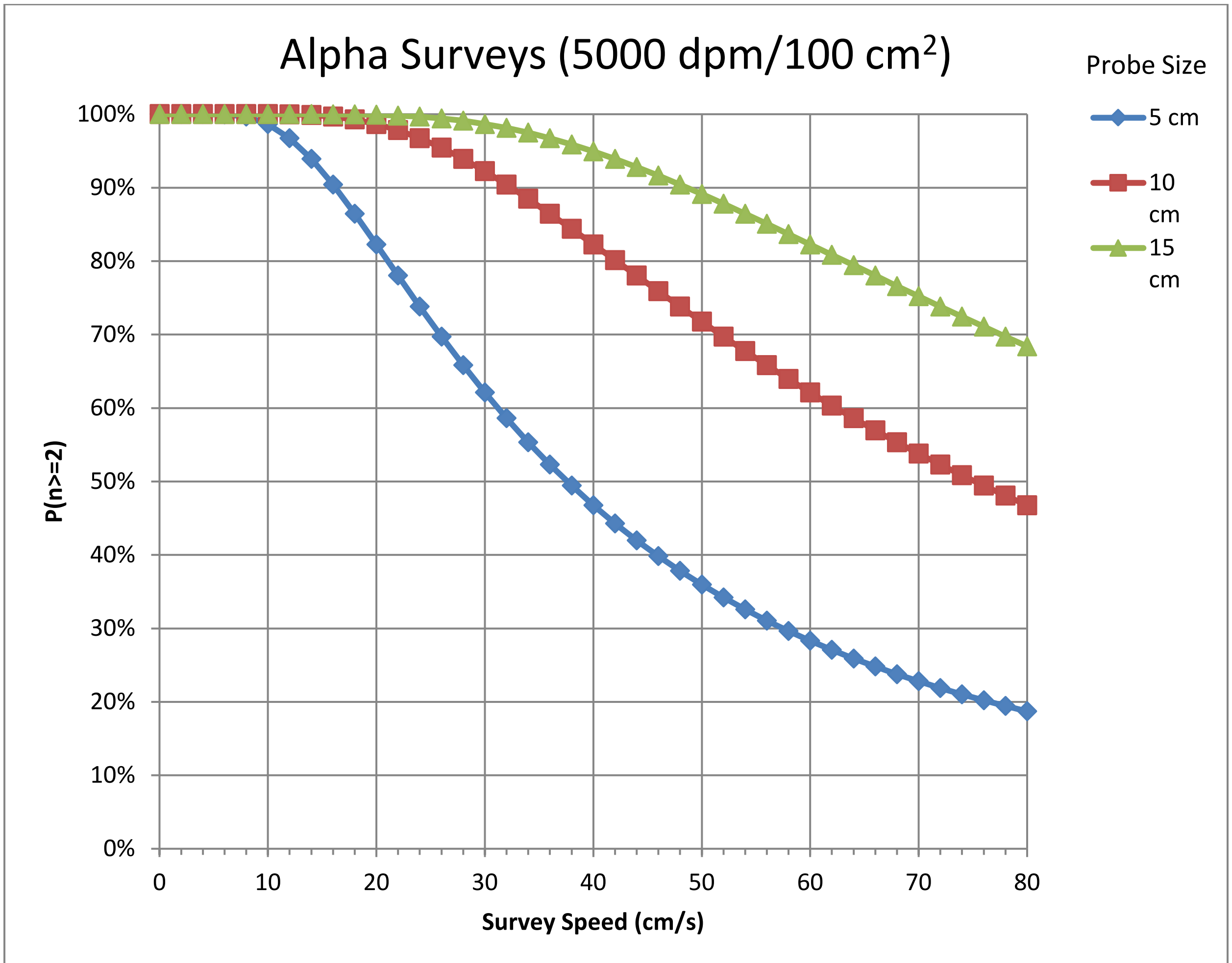


Figure J.6: Probability (P) of Getting Two or More Counts When Passing Over a 100 cm² Area Containing Residual Radioactive Material at 5,000 dpm/100 cm² Alpha

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.

K COMPARISON TABLES BETWEEN QUALITY ASSURANCE DOCUMENTS

The comparison tables in this appendix provide a reference for the MARSSIM user who may not be familiar with developing a Quality Assurance Project Plan (QAPP) based on EPA QA/R-5 (EPA 2001b).[1] The tables relate the basic recommendations and requirements of EPA QA/R-5 and other quality assurance documents with which the reader may be more familiar.

Each of the quality assurance documents compared in these tables was developed for a specific industry and scope. For this reason, there is not a direct comparison from one document to another. Rather, the tables are designed to show similarities between different quality assurance documents. In addition, there are topics specific to certain quality assurance documents that do not have a counterpart in these comparison tables.

If there is no section listed as being comparable with a section of EPA QA/R-5, then this does not necessarily mean that the topic is not covered by the quality assurance document. In some cases, the topic may have been divided up into several subtopics that are distributed among other sections of the particular document.

This appendix is not meant to provide a thorough cross-reference between different quality assurance documents. The purpose of these comparison tables is to demonstrate how the content of QAPPs might be arranged differently and show a user the location of important information concerning radiation surveys and site investigations. This might occur if the QAPP is developed using guidance with which the reviewer is unfamiliar.

EPA QA/R-5 is compared with five quality assurance documents in the following tables:

- EPA QAMS-005/80 (EPA 1980a)
- ASME NQA-1 (ASME 2017)
- DOE Order 414.1D (DOE 2011b)
- ISO 9000 (ISO 1987a)
- UFP-QAPP (EPA, DOD, and DOE 2005)

[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.

Table K-1: Comparison of EPA QA/R-5 and EPA QAMS-005/80

EPA QA/R-5 Elements		EPA QAMS-005/80	
A1	Title and Approval Sheet	1.0	Title Page with Provision for Approval Signatures
A2	Table of Contents	2.0	Table of Contents
A3	Distribution List		—
A4	Project/Task Organization	4.0	Project Organization and Responsibility
A5	Problem Definition/Background	3.0	Project Description
A6	Project/Task Description	3.0	Project Description
A7	Quality Objectives and Criteria	5.0	Quality Assurance Objectives for Measurement Data
A8	Special Training/Certification Requirements		—
A9	Documentation and Records		—
B1	Sampling Process Design (Experimental Design)	6.0	Sampling Procedures
B2	Sampling Methods	6.0	Sampling Procedures
B3	Sample Handling and Custody	7.0	Sample Custody
B4	Analytical Methods	9.0	Analytical Methods
B5	Quality Control	11.0	Internal Quality Control Checks and Frequency
B6	Instrument/Equipment Testing, Inspection, and Maintenance	13.0	Preventive Maintenance Procedures and Schedules
B7	Instrument/Equipment Calibration and Frequency	8.0	Calibration Procedures and Frequency
B8	Inspection/Acceptance of Supplies and Consumables		—
B9	Non-direct Measurements		—
B10	Data Management		—
C1	Assessments and Response Actions	12.0 15.0	Assessment and Response Actions Corrective Actions
C2	Reports to Management	16.0	Quality Assurance Reports to Management
D1	Data Review, Validation, and Verification Requirements	10.0	Data Reduction, Validation, and Reporting
D2	Validation and Verification Methods	10.0	Data Reduction, Validation, and Reporting
D3	Reconciliation with User Requirements		—

Table K-2: Comparison of EPA QA/R-5 and ASME NQA-1

EPA QA/R-5 Elements		ASME NQA-1 Elements	
A1	Title and Approval Sheet	—	
A2	Table of Contents	—	
A3	Distribution List	—	
A4	Project/Task Organization	1.	Organization
A5	Problem Definition/Background	—	
A6	Project/Task Description	3.	Design Control
A7	Quality Objectives and Criteria	2.	Quality Assurance Program
A8	Special Training/Certification Requirements	—	
A9	Documentation and Records	4. 6.	Procurement Document Control Document Control
B1	Sampling Process Design (Experimental Design)	3.	Design Control
B2	Sampling Methods	5.	Instructions, Procedures, and Drawings
B3	Sample Handling and Custody	13.	Handling, Storage, and Shipping
B4	Analytical Methods	5.	Instructions, Procedures, and Drawings
B5	Quality Control	9. 11.	Control of Processes Test Control
B6	Instrument/Equipment Testing, Inspection, and Maintenance	10. 12.	Inspection Control of Measuring and Test Equipment
B7	Instrument/Equipment Calibration and Frequency	14.	Inspection, Test, and Operating Status
B8	Inspection/Acceptance of Supplies and Consumables	7. 8.	Control of Purchased Items and Services Identification and Control of Items
B9	Non-direct Measurements	—	
B10	Data Management	—	
C1	Assessments and Response Actions	15. 16. 18.	Control of Nonconforming Items Corrective Action Audits
C2	Reports to Management	17.	Quality Assurance Records
D1	Data Review, Validation, and Verification Requirements	—	
D2	Validation and Verification Methods	—	
D3	Reconciliation with User Requirements	—	

Table K-3: Comparison of EPA QA/R-5 and DOE Order 414.1D

EPA QA/R-5 Elements		DOE Order 414.1D Elements	
A1	Title and Approval Sheet	—	
A2	Table of Contents	—	
A3	Distribution List	—	
A4	Project/Task Organization	3	Applicability
A5	Problem Definition/Background	1	Purpose
A6	Project/Task Description	1	Purpose
A7	Quality Objectives and Criteria	1	Purpose
A8	Special Training/Certification Requirements	4	Requirements
A9	Documentation and Records	4	Attachment 2
B1	Sampling Process Design (Experimental Design)	4	Requirements
B2	Sampling Methods	4	Requirements
B3	Sample Handling and Custody	—	
B4	Analytical Methods	—	
B5	Quality Control	4	Requirements
B6	Instrument/Equipment Testing, Inspection, and Maintenance	4	Requirements
B7	Instrument/Equipment Calibration and Frequency	—	
B8	Inspection/Acceptance of Supplies and Consumables	4 4	Attachment 2 Attachment 3
B9	Non-direct Measurements	4	Requirements
B10	Data Management	—	
C1	Assessments and Response Actions	5	Responsibilities
C2	Reports to Management	5	Responsibilities Also see Attachment 2
D1	Data Review, Validation, and Verification Requirements	—	
D2	Validation and Verification Methods	—	
D3	Reconciliation with User Requirements	—	

Table K-4: Comparison of EPA QA/R-5 and ISO 9000

EPA QA/R-5 Elements		ISO 9000 Elements	
A1	Title and Approval Sheet	—	
A2	Table of Contents	—	
A3	Distribution List	—	
A4	Project/Task Organization	4	Management Responsibility
A5	Problem Definition/Background	—	
A6	Project/Task Description	—	
A7	Quality Objectives and Criteria	5 5.2	Quality System Principles Structure of the Quality System
A8	Special Training/Certification Requirements	—	
A9	Documentation and Records	—	
B1	Sampling Process Design (Experimental Design)	8	Quality in Specification and Design
B2	Sampling Methods	10	Quality in Production
B3	Sample Handling and Custody	16	Handling and Post Production Functions
B4	Analytical Methods	10	Quality in Production
B5	Quality Control	11	Control of Production
B6	Instrument/Equipment Testing, Inspection, and Maintenance	13	Control of Measuring and Test Equipment
B7	Instrument Calibration and Frequency	—	
B8	Inspection/Acceptance of Supplies and Consumables	9 11.2	Quality in Procurement Material Control and Traceability
B9	Non-direct Measurements	—	
B10	Data Management	—	
C1	Assessments and Response Actions	5.4 14 15	Auditing the Quality System Nonconformity Corrective Action
C2	Reports to Management	5.3 6	Documentation of the Quality System Economics—Quality Related Costs
D1	Data Review, Validation, and Verification Requirements	11.7	Control of Verification Status
D2	Validation and Verification Methods	12	Verification Status
D3	Reconciliation with User Requirements	—	
—		7	Quality in Marketing

1 **Table K-5: Comparison of EPA QA/R-5 and UFP-QAPP**

EPA QA/R-5 Elements		UFP-QAPP Elements	
A1	Title and Approval Sheet	2.1	Title and Approval Page
A2	Table of Contents	2.2	Document Format and Table of Contents
A3	Distribution List	2.3	Distribution List and Project Personnel Sign-Off Sheet
A4	Project/Task Organization	2.4	Project Organization
A5	Problem Definition/Background	2.5	Project Planning/Problem Definition
A6	Project/Task Description	—	
A7	Quality Objectives and Criteria	2.6	Project Quality Objectives and Measurement Performance Criteria
A8	Special Training/Certification Requirements	2.4.4	Special Training Requirements and Certification
A9	Documentation and Records	3.5.1	Project Documentation and Records
B1	Sampling Process Design (Experimental Design)	3.1.1	Sampling Process Design and Rationale
B2	Sampling Methods	3.1.2	Sampling Procedures and Requirements
B3	Sample Handling and Custody	3.3	Sample Collection Documentation, Handling, Tracking, and Custody Procedures
B4	Analytical Methods	3.2	Analytical Tasks
B5	Quality Control	3.4	Quality Control Samples
B6	Instrument/Equipment Testing, Inspection, and Maintenance	3.1.2.4 3.2.3	Field Equipment Calibration, Maintenance, Testing, and Inspection Procedures Analytical Instrument and Equipment Maintenance, Testing, and Inspection Procedures
B7	Instrument Calibration and Frequency	3.1.2.4 3.2.2	Field Equipment Calibration, Maintenance, Testing, and Inspection Procedures Analytical Instrument Calibration
B8	Inspection/Acceptance of Supplies and Consumables	3.1.2.5 3.2.4	Sampling Supply Inspection and Acceptance Procedures Analytical Supply Inspection and Acceptance Procedures
B9	Non-direct Measurements	—	
B10	Data Management	3.5	Data Management Tasks
C1	Assessments and Response Actions	4.1	Assessments and Response Actions
C2	Reports to Management	4.2	QA Management Reports
D1	Data Review, Validation, and Verification Requirements	5.2.1 5.2.2	Step I: Verification Step II: Validation
D2	Validation and Verification Methods	5.2.1 5.2.2	Step I: Verification Step II: Validation
D3	Reconciliation with User Requirements	5.2.3	Step III: Usability Assessment
—		2.8	Project Overview and Schedule
—		5.3	Streamlining Data Review

2

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 generate a crude histogram of the data quickly. The "stems" of such a display are the most significant digits of the data. Consider the sample data of **Section 8.2.2.2:**

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 is too few stems to be informative, just as three intervals would be too few for constructing 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. 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. In order to ensure this, the same number of digits should 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).

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. Further information on the construction and interpretation of data plots is given in EPA QA/G-9S (EPA 2006b).

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

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:

$$\text{Percent} = \frac{100\ (\text{rank-0.5})}{(\text{number of data points})} \qquad \text{(L-1)}$$

The results for the example data of **Section L.1** are shown in **Table L.1.** The quantile plot for this example is shown in **Figure L.2.**

The slope of the curve in the quantile plot is an indication of 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: 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

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. These are shown as the dashed lines in **Figure L.2.** 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 and ~88, respectively, 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 to judging the symmetry of the data distribution. There are no especially unusual features in the example quantile plot shown in **Figure L.2,** other than the possibility of slight asymmetry around the median.

Another quantile plot, for the example data of **Section 8.3.2,** is shown in **Figure L.3.**

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, $j = 1, \dots n$, with the distribution of the reference area data X_i , $i = 1, \dots m$. (If the reference area data set 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, we obtain the results in **Table L.2.**

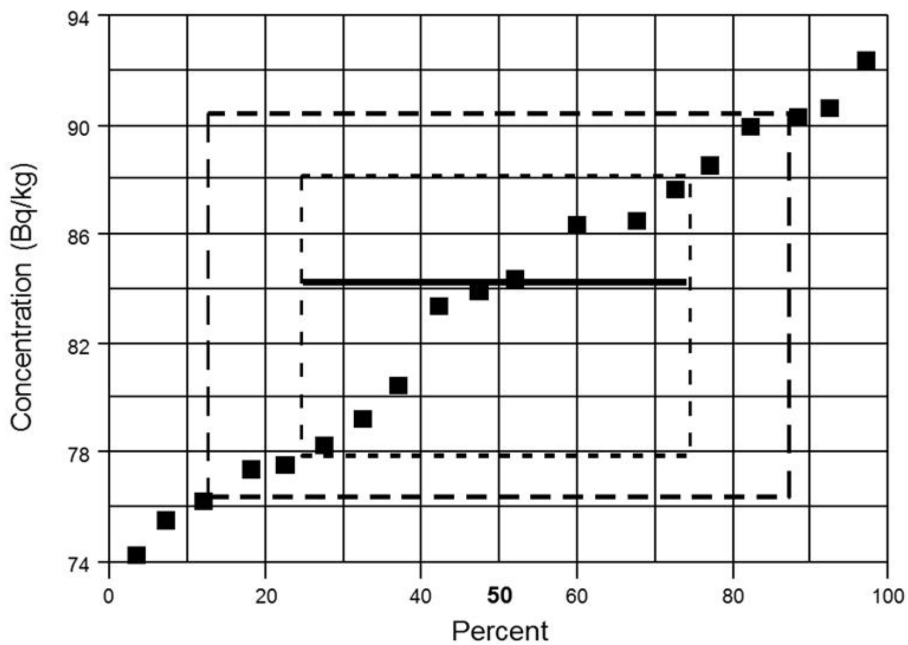


Figure L-2: Example of a Quantile Plot

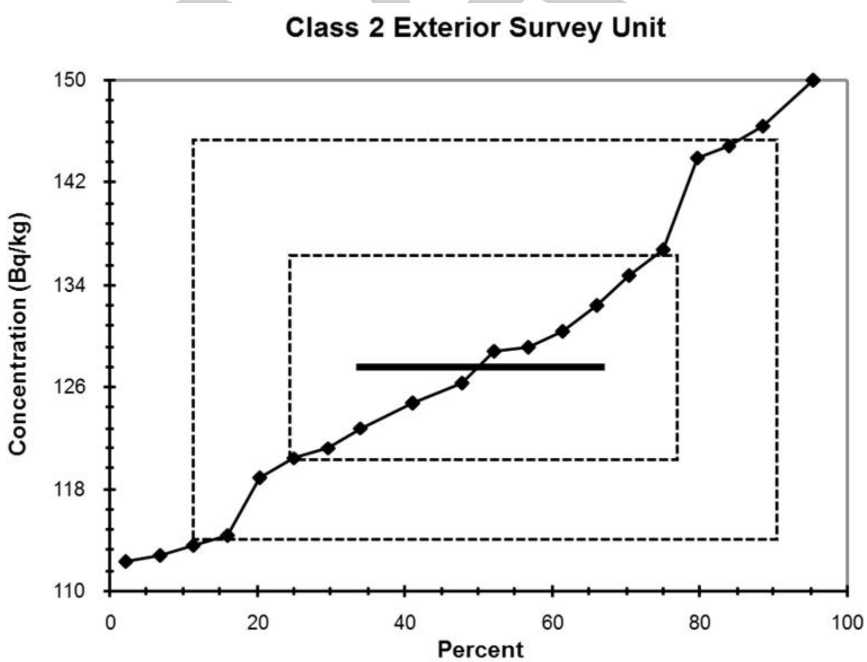


Figure L-3: Quantile Plot for Example Class 2 Exterior Survey Unit of Section 8.3.2

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 is 80.7, and the sample standard deviation is 7.5.

For the larger data set, the data must be interpolated to match the number of points in the smaller data set. This is done by computing v_i:

$$v_1 = 0.5(^n/_m) + 0.5 \text{ and } v_{i+1} = v_i + (^n/_m) \text{ for } i = 1, \cdots m - 1 \qquad \text{(L-2)}$$

where m is the number of points in the smaller data set and n is the number of points in the larger data set. For each of the ranks, $i,$ in the smaller data set, a corresponding value in the larger data set 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:

$$Z_i = (1 - g)Y_j + gY_{j+1} \qquad \text{(L-3)}$$

Using Y values from **Table L.1,** the results of these calculations are shown in **Table L.3.**

Finally, Z_i is plotted against X_i to obtain the quantile-quantile plot. This example from **Table L.3** is shown in **Figure L.4.** The quantile-quantile plot is valuable because it provides a direct visual comparison of the two data sets. 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, is an indication 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[1] be tested using the nonparametric statistical tests described in **Chapter 8.**

Another quantile-quantile plot, for the Class 1 Interior Survey Unit example data, is shown in **Figure A.8.** Further information on the interpretation of quantile and quantile-quantile plots is given in EPA QA/G-9S (EPA 2006b).

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	—	—	—

[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.

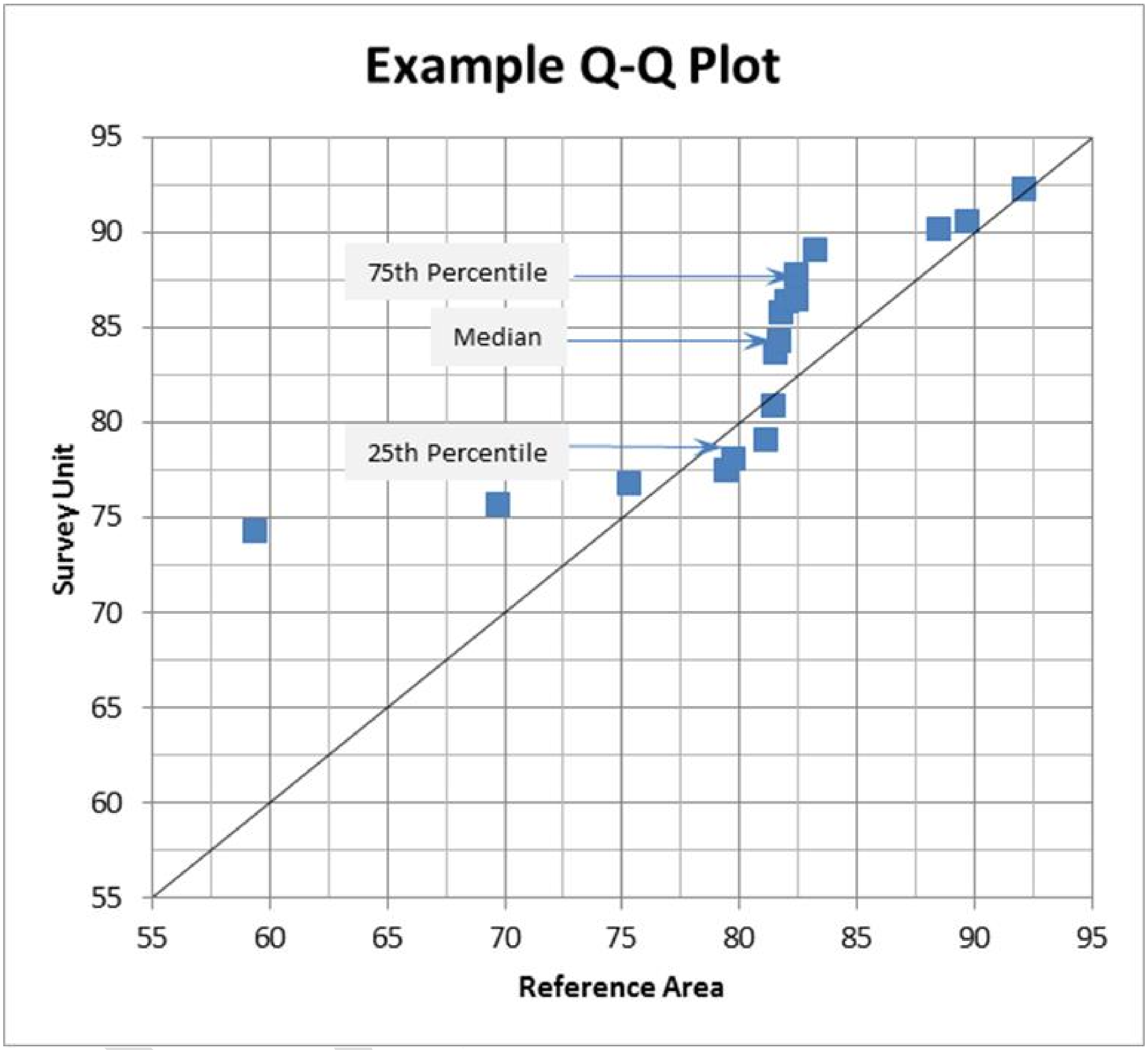


Figure L-4: Example Quantile-Quantile Plot

M CALCULATION OF POWER CURVES

M.1 Power Calculations for the Statistical Tests

M.1.1 Power of the Sign Test

The power of the Sign test, $1-\beta$, for rejecting the null hypothesis, may be found using **Equation M-1:**

$$1-\beta = 1-\sum_{i=0}^{k}\binom{N}{i}[q^*]^i[1-q^*]^{N-i} = 1-\Phi\left(\frac{k-Nq^*}{\sqrt{Nq^*(1-q^*)}}\right) \qquad \text{(M-1)}$$

where N is the number of samples, k is the critical value, and

$$q^* = \Phi(\Delta/\sigma) \qquad \text{(M-2)}$$

where Δ/σ is the relative shift. The function $\Phi(z)$ is the standard cumulative normal distribution function tabulated in **Table I.1.** 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. 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.

Note that if Δ/σ is large, q^* approaches one, and the power also approaches one. 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 standard deviation of the actual measurement data, s, in order to construct a retrospective power curve for the test. This is an important step when the null hypothesis is not rejected, because it demonstrates whether the data quality objectives (DQOs) have been met.

The retrospective power curve for the Sign test can be constructed using **Equations M-1 and M-2**, together with the actual number of concentration measurements obtained, N. The power as a function of Δ/σ is calculated, where s is the observed standard deviation. The values of Δ/σ are converted to concentration using:

$$\text{Concentration} = \text{DCGL}_\text{W} - (\Delta/\sigma)\times s \qquad \text{(M-3)}$$

The results for **Section 8.3.2, Example 6** (Class 3 Exterior Survey Unit), are plotted in **Figure M.1.** This figure shows the probability that the survey unit would have passed the release criteria using the Sign test versus concentration of residual radioactive material. This curve shows that the DQOs were met, despite the fact that the actual standard deviation was larger than that used in designing the survey. This is primarily due to the additional 20 percent that was added to the sample size, and also that sample sizes were always rounded up. The curve shows that a survey unit with less than 135 becquerels per kilogram (Bq/kg) would almost always pass, and that a survey unit with more than 145 Bq/kg would almost always fail.

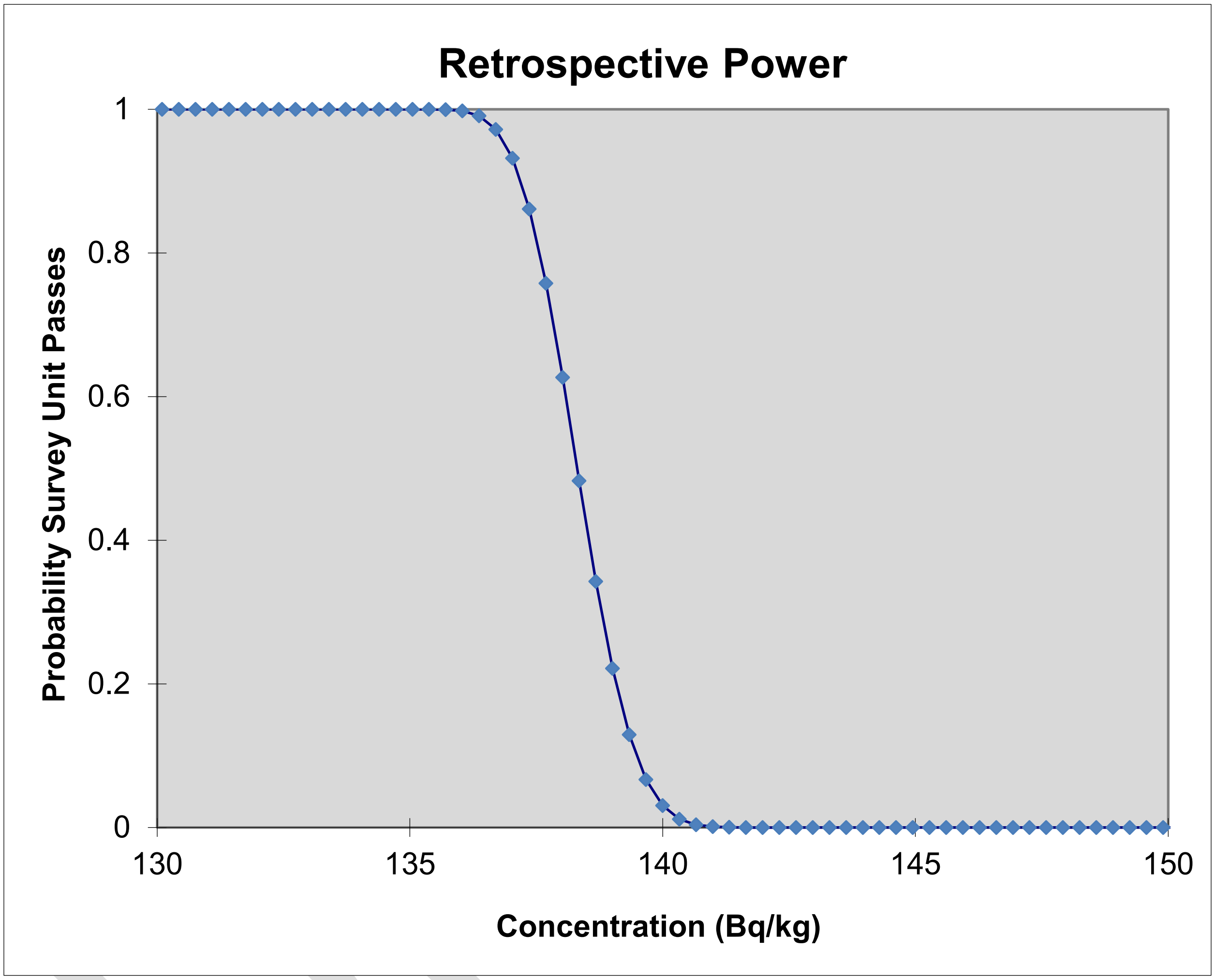


Figure M-1: Retrospective Power Curve for Class 3 Exterior Survey Unit

M.1.2 Power of the Wilcoxon Rank Sum (WRS) Test

The power $(1-\beta)$ of the WRS test is computed from

$$1-\beta = 1-\Phi\left[\frac{W_c - 0.5 - 0.5m(m+1) - E(W_{MW})}{\sqrt{\mathrm{Var}(W_{MW})}}\right] \quad \text{(M-4)}$$

where W_c is the critical value found in **Table I.5** for the appropriate vales of α, n, and m. Values of $\Phi(z)$, the standard normal cumulative distribution function, are given in Table I.1.

$W_{MW} = W_r - 0.5m(m+1)$ is the Mann-Whitney form of the WRS test statistic. Its mean is

$$E(W_{MW}) = mnP \qquad \text{(M-5)}$$

and its variance is

$$\mathrm{Var}(W_{MW}) = mnP_r(1-P_r) + mn(n+m-2)(p_2 - P_r^2) \qquad \text{(M-6)}$$

Values of P_r and p_2 as a function of Δ/σ are given in **Table M.1.**

The power calculated in **Equation M-4** is an approximation, but the results are generally accurate enough to be used to determine if the sample design achieves the DQOs.

The retrospective power curve for the WRS test can be constructed using **Equation M-4, Equation M-5,** and **Equation M-6,** together with the actual number of concentration measurements obtained, N. The power as a function of Δ/σ is calculated. The values of Δ/σ are converted to concentration using Equation M-3.

Example 1: Class 2 Interior Drywall Survey Unit

The results for this example are plotted in **Figure M.2,** showing the probability that the survey unit would have passed the release criterion using the WRS test versus concentration of residual radioactive material. This curve shows that the data quality objectives were easily achieved. The curve shows that a survey unit with less than 4,500 decays per minute (dpm)/100 square centimeters (cm^2) above background would almost always pass, and that one with more than 5,100 dpm/100 cm^2 above background would almost always fail.

Table M-1: Values of P_r and p_2 for Computing the Mean and Variance of W_{MW}

Δ/σ	P_r	p_2	Δ/σ	P_r	p_2
-6.0	1.11×10^{-5}	1.16×10^{-7}	0.7	0.689691	0.544073
-5.0	0.000204	6.14×10^{-6}	0.8	0.714196	0.574469
-4.0	0.002339	0.000174	0.9	0.737741	0.604402
-3.5	0.006664	0.000738	1.0	0.760250	0.633702
-3.0	0.016947	0.002690	1.1	0.781662	0.662216
-2.5	0.038550	0.008465	1.2	0.801928	0.689800
-2.0	0.078650	0.023066	1.3	0.821015	0.716331
-1.9	0.089555	0.027714	1.4	0.838901	0.741698
-1.8	0.101546	0.033114	1.5	0.855578	0.765812
-1.7	0.114666	0.039348	1.6	0.871050	0.788602
-1.6	0.128950	0.046501	1.7	0.885334	0.810016
-1.5	0.144422	0.054656	1.8	0.898454	0.830022
-1.4	0.161099	0.063897	1.9	0.910445	0.848605
-1.3	0.178985	0.074301	2.0	0.921350	0.865767
-1.2	0.198072	0.085944	2.1	0.931218	0.881527
-1.1	0.218338	0.098892	2.2	0.940103	0.895917
-1.0	0.239750	0.113202	2.3	0.948062	0.908982
-0.9	0.262259	0.128920	2.4	0.955157	0.920777
-0.8	0.285804	0.146077	2.5	0.961450	0.931365
-0.7	0.310309	0.164691	2.6	0.967004	0.940817
-0.6	0.335687	0.184760	2.7	0.971881	0.949208
-0.5	0.361837	0.206266	2.8	0.976143	0.956616
-0.4	0.388649	0.229172	2.9	0.979848	0.963118
-0.3	0.416002	0.253419	3.0	0.983053	0.968795
-0.2	0.443769	0.278930	3.1	0.985811	0.973725
-0.1	0.471814	0.305606	3.2	0.988174	0.977981
0.0	0.500000	0.333333	3.3	0.990188	0.981636
0.1	0.528186	0.361978	3.4	0.991895	0.984758
0.2	0.556231	0.391392	3.5	0.993336	0.987410
0.3	0.583998	0.421415	4.0	0.997661	0.995497
0.4	0.611351	0.451875	5.0	0.999796	0.999599
0.5	0.638163	0.482593	6.0	0.999989	0.999978
0.6	0.664313	0.513387			

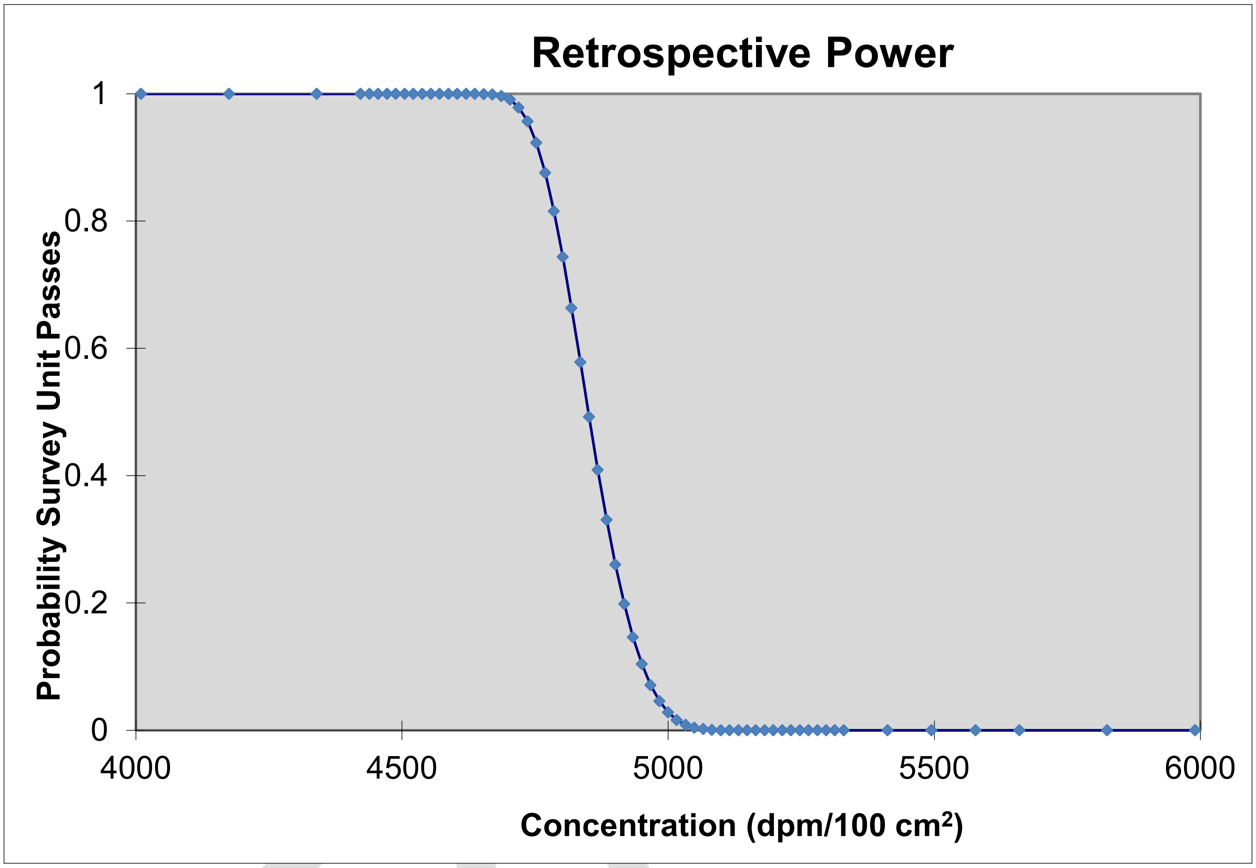


Figure M-2: Retrospective Power Curve for Class 2 Interior Drywall Survey Unit

N EFFECT OF PRECISION ON PLANNING AND PERFORMING SURVEYS

N.1 Introduction

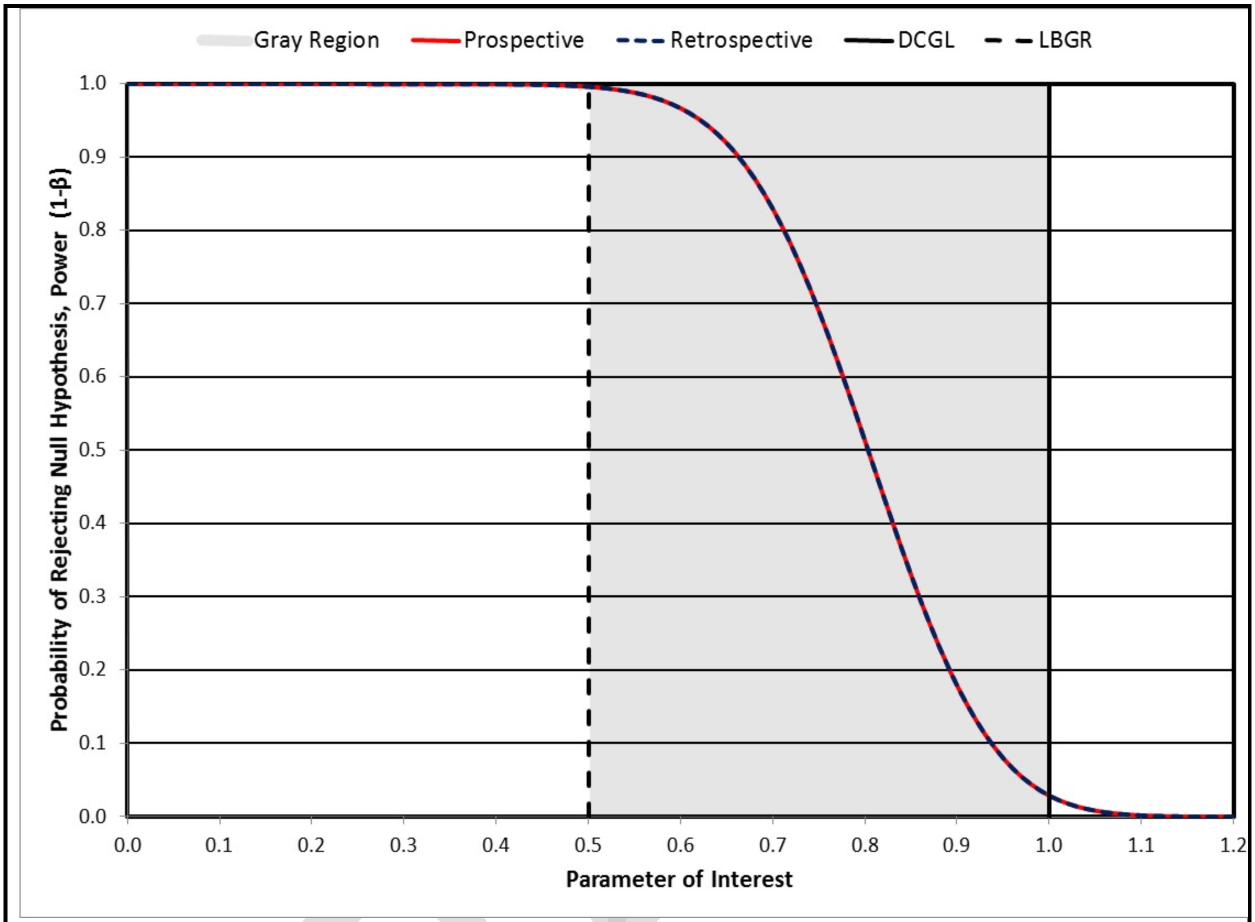
This appendix includes three illustrative examples demonstrating the potential consequences of using methods with different levels of precision for planning and designing a Final Status Survey (FSS) and for actually performing the FSS. **Example 1** illustrates the use of precise measurement methods for planning and performing the FSS. The use of less precise measurement methods for both planning and performing the FSS is illustrated in **Example 2**. **Example 3** illustrates the use of a precise measurement method for planning and a less precise method for performing the FSS.

Example 1: Precise Measurements Methods Used for Both Planning and Performing 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, 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 vs. 0.5) as shown in the table below.

Measurement Method	
Precise	**Precise**
Population Parameters	
Planning (DCGL = 1)	Assessment (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, a relatively minor loss of power at the actual, observed mean concentration.



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

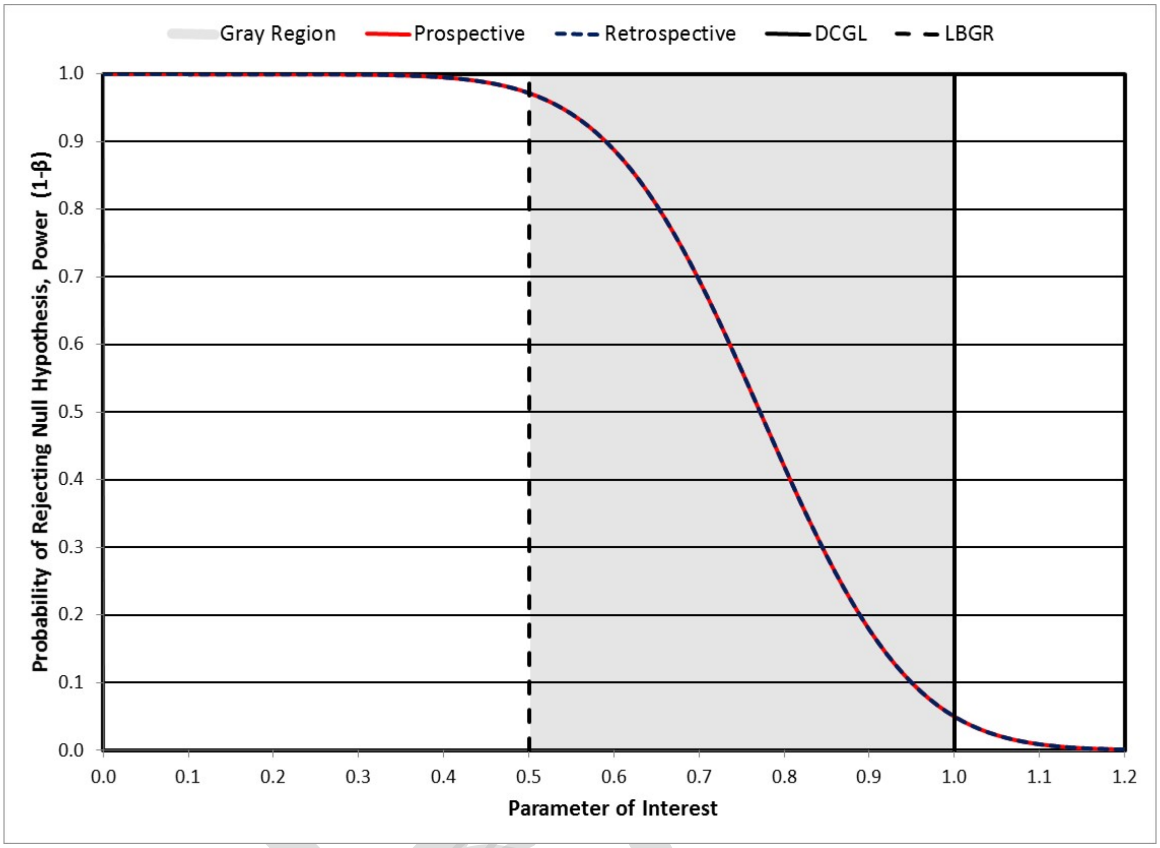
Example 2: Less Precise Measurement Methods Used for Both Planning and Performing the FSS

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 **Example 1,** but in this case the σ increased compared to **Example 1,** due to the less precise measurements as shown in the table.

Measurement Method	
Less Precise	**Less Precise**
Population Parameters	
Planning (DCGL = 1)	Assessment (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 1** due to the higher σ associated with the less precise measurement technique, the retrospective power of

0.83 seen in **Example 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 1.



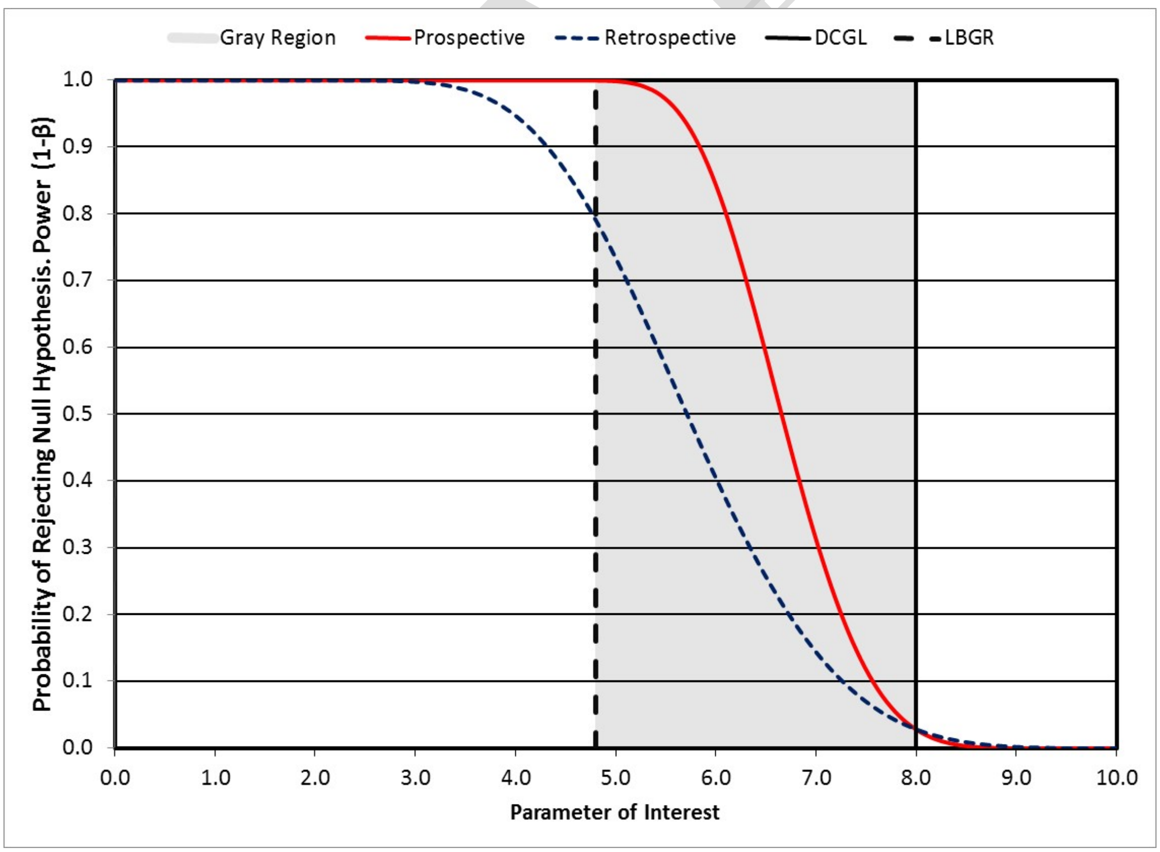
Prospective and Retrospective Power Curves for $N = 30$, $\alpha = 0.05$. and $\sigma = 0.6$

Example 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 Ranked 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 final status survey 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 variability.

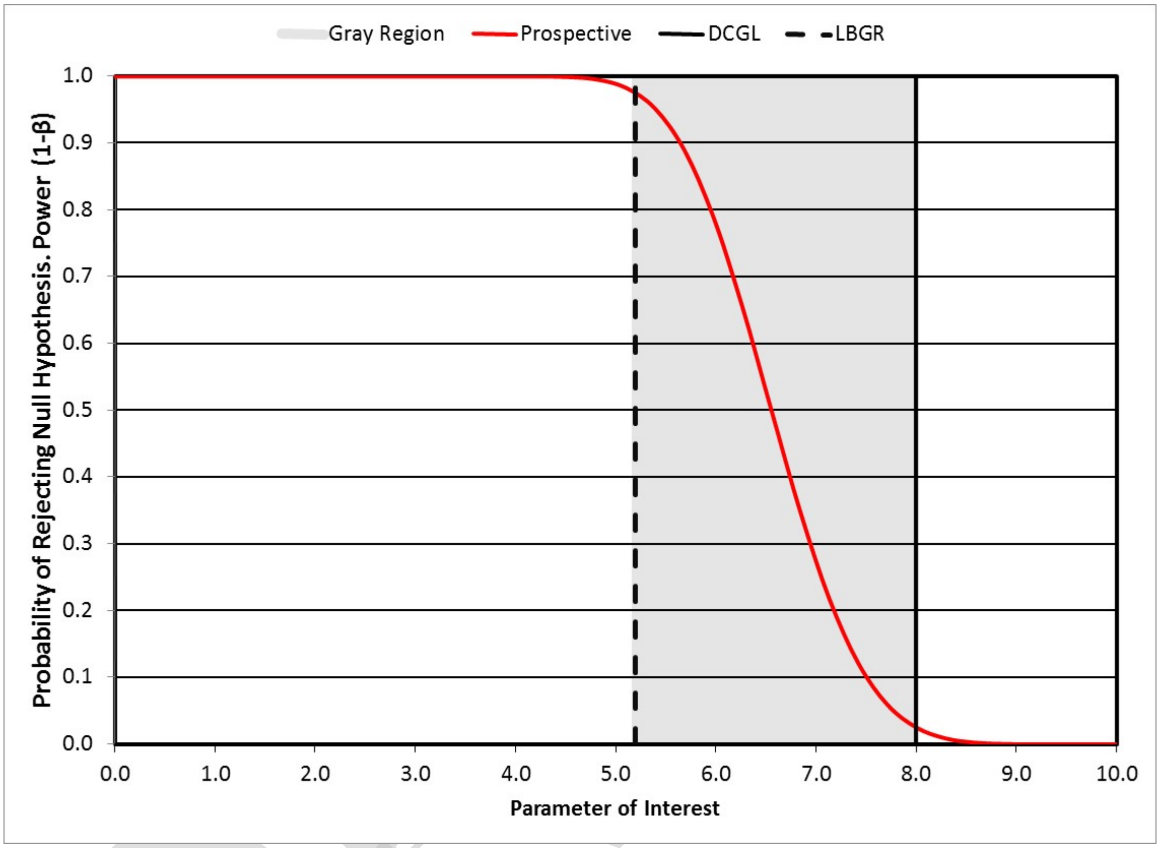
Measurement Method	
Precise	**Less Precise**
Population Parameters	
Planning (DCGL = 8)	Assessment (DCGL = 8)
$\bar{x} \pm \sigma = 4.8 \pm 1.7$ $N/2 = 14$	$\bar{x} \pm \sigma = 5.2 \pm 2.9$ $m = n = 14$

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 $\sigma = 2.9$

N.2 Summary

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 and more survey units than expected may fail due to insufficient survey design, thereby requiring that survey units be resurveyed. 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. The planning team should[1] 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

[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.

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 make up for the greater uncertainty of the less precise measurements.

O DETAILED CALCULATIONS FOR STATISTICAL TESTS AND ILLUSTRATIVE EXAMPLES FOR THE DETERMINATION OF DCGLS

O.1 Introduction

The first part of this appendix explains the method used to determine the number of data points (direct measurements or samples) for the WRS test and Sign test. The WRS test is used when residual radioactive material is present in the background or 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 or when measurements are radionuclide-specific or if background levels are a small fraction of the Derived Concentration Guideline Level (DCGL).

The second part of the appendix provides illustrative examples of the determination of DCGLs for the elevated measurement comparison ($DCGL_{EMC}$s) for outdoor and indoor survey units. Exposure pathway modeling is used to calculate the $DCGL_{EMC}$ as a function of the area of radioactive material. The final two parts of the appendix include information for the release of discrete radioactive particles and sites covered by the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA).

O.2 The WRS Test

The steps required to determine the number of data points for the WRS test are described below. The WRS test can be used for 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.

O.2.1 Determine P_r

The probability that a random measurement from the survey unit exceeds a random measurement from the background reference area by less than the $DCGL_W$ when the survey unit median is equal to the Lower Bound of the Gray Region (LBGR) above background is defined as P_r. P_r is used in **Equation O-1** for determining the number of measurements to be performed during the survey (see also **Section 5.3.3**). **Table O.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 O.1.** Information on calculating individual values of P_r is available in NUREG-1505 (NRC 1998a). If the actual value of the relative shift is not listed in Table O.1, always select the next lower value that appears in the table. For example, $\Delta/\sigma = 1.67$ does not appear in **Table O.1.** The next lower value is 1.6, so the value of P_r would be 0.871014.

Table O.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	0.528182	1.4	0.838864
0.2	0.556223	1.5	0.855541
0.3	0.583985	1.6	0.871014

[1] If Δ/σ > 4.0, use P_r = 1.000000

Δ/σ	P_r	Δ/σ	P_r
0.4	0.611335	1.7	0.885299
0.5	0.638143	1.8	0.898420
0.6	0.664290	1.9	0.910413
0.7	0.689665	2.0	0.921319
0.8	0.714167	2.25	0.944167
0.9	0.737710	2.5	0.961428
1.0	0.760217	2.75	0.974067
1.1	0.781627	3.0	0.983039
1.2	0.801892	3.5	0.993329
1.3	0.820978	4.0	0.997658

O.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 (see **Table O.2**). $Z_{1-\alpha}$ and $Z_{1-\beta}$ are standard statistical values (Harnett 1975).

Table O.2: Percentiles Represented by Selected Values of α and β

α (or β)	$Z_{1-\alpha}$ (or $Z_{1-\beta}$)	α (or β)	$Z_{1-\alpha}$ (or $Z_{1-\beta}$)
0.005	2.576	0.10	1.282
0.01	2.326	0.15	1.036
0.015	2.241	0.20	0.842
0.025	1.960	0.25	0.674
0.05	1.645	0.30	0.524

O.2.3 Calculate Number of Data Points for WRS 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:

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

The value of N calculated using **Equation O-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 O-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 (see **Appendix M**). When the Quantile test is applied in Scenario B, the sample size for the WRS test is used.

O.3 The Sign Test

The steps required to determine the number of data points for the Sign test are described below. The Sign test is only used for Scenario A.

O.3.1 Determine P_s

P_s is the estimated probability that a random measurement from the survey unit will be less than the Upper Bound of the Gray Region (UBGR)—equal to the discrimination level—when the survey unit median is actually at the LBGR—equal to the action level—and is only used when the radionuclide is not present in background. P_s is used in **Equation O-2** to calculate the minimum number of data points necessary for the survey to meet the data quality objectives (DQOs). The value of the relative shift calculated in **Section 5.3** is used to obtain the corresponding value of P_s from **Table O.3.**

O.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 (see **Table O.2**).

O.3.3 Calculate Number of Data Points for Sign Test

The number of data points, N, to be obtained for the Sign test is next calculated using the following formula:

$$N = \frac{(Z_{1-\alpha} + Z_{1-\beta})^2}{4(P_s - 0.5)^2} \qquad \text{(O-2)}$$

Finally, the number of anticipated data points should be increased by at least 20 percent as discussed in **Section O.2.3** to ensure sufficient power of the tests and to allow for possible data losses.

[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.

Table O.3: Values of P_s for Given Values of the Relative Shift, Δ/σ, When the Radionuclide Is Not Present in Background[3]

Δ/σ	P_s	Δ/σ	P_s
0.1	0.539828	1.2	0.884930
0.2	0.579260	1.3	0.903199
0.3	0.617911	1.4	0.919243
0.4	0.655422	1.5	0.933193
0.5	0.691462	1.6	0.945201
0.6	0.725747	1.7	0.955435
0.7	0.758036	1.8	0.964070
0.8	0.788145	1.9	0.971284
0.9	0.815940	2.0	0.977250
1.0	0.841345	2.5	0.993790
1.1	0.864334	3.0	0.998650

O.4 Calculating Area Factors and the DCGL for the EMC

O.4.1 Background

The term "area factor" has been used to account for the factor by which a DCGL, which is typically calculated assuming a uniform concentration over the entire area of the survey unit, could be exceeded for a smaller area of elevated radioactivity. In this document, the DCGL for a survey unit is differentiated from the DCGL for an elevated area using the subscripts "w" for wide area ($DCGL_w$), and "EMC" for elevated measurement comparison ($DCGL_{EMC}$), respectively. Using this naming convention,

$$DCGL_{EMC} = DCGL_W \times \text{Area Factor} \quad \text{(O-3)}$$

MARSSIM recommends use of dose or risk modeling to determine $DCGL_{EMC}$ rather than use of published area factors. However, because the area factor concept is useful for communicating the influence of area on the $DCGL_W$, published area factors intended for illustrative purposes only were provided in previous versions of MARSSIM. Because these area factors were misused for specific problems, the term "area factor" is largely omitted from the main body of this report. Historical information on the use of area factors is provided in this appendix for completeness.

O.4.2 Historical Use of Area Factors

The first effort to establish release criteria for areas of elevated radioactive material, by the Atomic Energy Commission (AEC) in 1974, simply used a factor of three above the average for surficial radioactive material (NRC 1974). A subsequent effort proposed by the Department of Energy (DOE) led to an approach that could be employed in the field. Applying this approach, the following formula is used to assess the factor by which the DCGL can be increased for the smaller area (Yu et al. 1993, Yu et al. 2001):

[3] If $\Delta/\sigma > 3.0$, use $P_s = 1.000000$

$$F = \sqrt{\frac{100}{A}} \qquad \text{(O-4)}$$

In this equation, F is the multiplicative area factor and A is the area of radioactive material in square meters. A is recommended to be no greater than 25 m^2 and not less than 1 m^2 (for additional details see Equation 3.17 and Table 3.3 in [Yu et al. 2001][4]). This approach is based upon the external gamma radiation exposure pathway and does not consider other pathways. In general, area factors derived based on the external gamma radiation pathway are the most limiting area factors for elevated areas of radioactive material. In other words, for external radiation, the approach is generally protective and may be more limiting when other pathways (pathways other than external radiation) dominate the dose from radionuclides present at the site.[5]

O.4.3 Special Considerations

MARSSIM presents a risk- and dose-based approach to elevated areas of radioactive material (see **Sections 5.3.5 and 5.3.6**). This treatment of elevated areas of radioactive material is more comprehensive than that of the AEC guide for surficial radioactive material (NRC1974) or the DOE approach for soil (Yu et al. 1993) and is one conservative approach to assess areas of elevated radioactive materials. However, in certain cases, the MARSSIM approach may be overly conservative and use of other approaches may be desirable to develop $DCGL_{EMC}$. For example, **Equation 8-4** indicates that the sum of fractions for each radionuclide, source, and elevated area, as applicable, should be summed to assess compliance with the release criteria. This approach can be overly conservative in certain cases (e.g., if several DCGLs are developed for use in **Equation 8-4** without modification of occupancy times, an analyst may be inadvertently assuming that a receptor is located in the center of multiple elevated areas and in the larger survey unit at the same time leading to unrealistic, if not physically impossible exposure times).

Abelquist (2008 and 2010) compared various approaches for addressing elevated areas of radioactive material. Abelquist calculated area factors that were significantly higher than those calculated using other approaches. Abelquist's work provides support for use of alternative approaches to considering elevated areas of residual radioactive material when traditional methods yield unacceptable results. Guidance on consideration of elevated areas of residual radioactivity also is found in NUREG-1757, Volume 2 (see Chapter 5 and Appendix I). If elevated areas are risk-significant for a particular site, it is recommended that the cognizant regulatory agency be consulted to determine acceptable methods for addressing elevated areas.

[4] The "User's Manual for RESRAD, Version 6" states that for larger hot spot areas (≥100 m^2) the release criteria for the entire site should be used. The "manual" also suggests that the hot spot guidelines should not exceed 10 times the authorized limit, and that every reasonable effort should be made to identify and remove any source that has a radionuclide concentration exceeding 30 times the authorized limit, irrespective of area (Yu et al. 2001).

[5] If the external gamma radiation pathway is not important for the mix of radionuclides present at a site, this approach is not recommended. Additionally, area factors provided in NUREG-1505 and in Table O.4 of this report may be more limiting than the use of Equation O-4 for certain radionuclides. Thus, exposure pathway modeling is recommended for development of area factors.

O.4.4 Historical Examples Using Area Factors

$DCGL_{EMC}$s are generated using exposure pathway models for specific areas and nuclides. **Tables O.4 and O.5** provide the multiplicative factor that can be applied to the $DCGL_W$ to determine a $DCGL_{EMC}$ that corresponds to the equivalent dose or risk, represented by a higher activity concentration but in a smaller area. These factors are called area factors. The $DCGL_W$ and $DCGL_{EMC}$s for outdoor areas were calculated using RESRAD 6.5 (Yu et al. 2001, Yu et al. 2007, NRC 2000a, NRC 2000c), and the $DCGL_{EMC}$ is divided by the $DCGL_W$ to calculate the factors listed in **Table O.4.** For each radionuclide, the dose from all applicable exposure pathways was calculated assuming a fixed concentration of the radionuclides. The area of residual radioactive material in RESRAD 6.5 defaults to 10,000 m^2. Other than changing the area (i.e., 1, 3, 10, 30, 100, 300, 1,000, or 3,000 m^2) and conforming changes to the length parallel to aquifer flow parameter (for when the non-dispersion model is selected), the RESRAD default values were not changed. RESRAD-BUILD 3.5 (Yu et al. 2003, NRC 2000a, NRC 2000c) was used to calculate $DCGL_W$ and $DCGL_{EMC}$s for indoor areas, and the $DCGL_{EMC}$ divided by the $DCGL_W$ was used to calculate the factors listed in **Table O.5**. The area of residual radioactive material in RESRAD-BUILD 3.5 defaults to 36 m^2 for an assumed building floor. The other areas compared to this value were 1, 4, 9, 16, or 25 m^2. Removable surface radioactive material was assumed to be 10 percent. No other changes to the default values were made. Note that the use of RESRAD to determine the factors is for illustration purposes only. In the case of RESRAD-BUILD, the factors for wall or ceiling activity would be different than those shown in **Table O.5** because of the different geometry. The MARSSIM user should consult with the regulatory agency for guidance on acceptable techniques to determine $DCGL_{EMC}$s for smaller areas of elevated residual radioactive material.

Table O.4: Illustrative Examples of Outdoor Area Factors[6]

Nuclide	Area (m^2)								
	1	3	10	30	100	300	1,000	3,000	10,000
^{241}Am	120	42	14	5.1	1.8	1.2	1.0	1.0	1.0
^{60}Co	9.7	4.4	2.1	1.5	1.2	1.1	1.1	1.0	1.0
^{137}Cs	11	4.9	2.4	1.8	1.4	1.2	1.1	1.1	1.0
^{63}Ni	1600	540	190	56	17	5.6	1.7	1.5	1.0
^{226}Ra & progeny w/radon	60	23	8.5	3.4	1.2	1.1	1.0	1.0	1.0
^{226}Ra & progeny, w/o radon	25	11	5.3	3.6	2.7	1.9	1.0	1.0	1.0
^{232}Th & progeny	19	8.6	4.2	3.0	2.2	1.6	1.0	1.0	1.0
^{238}U	89	41	21	15	11	4.4	1.3	1.0	1.0

6 The values listed in **Table O.4** are for illustrative purposes only. Consult regulatory guidance to determine area factors to be used for compliance demonstration. Minor changes in modeling assumptions can result in large changes in area factors. Further, the default input parameters may not be appropriate or suitable for many sites.

Table O.5: Illustrative Examples of Indoor Area Factors[7]

Nuclide	Area (m^2)					
	1	4	9	16	25	36
^{241}Am	36.0	9.0	4.0	2.2	1.4	1.0
^{60}Co	9.2	3.1	1.9	1.4	1.2	1.0
^{137}Cs	9.4	3.2	1.9	1.4	1.2	1.0
^{63}Ni	36.0	9.0	4.0	2.3	1.4	1.0
^{226}Ra	18.1	5.5	2.9	1.9	1.3	1.0
^{232}Th	36.0	9.0	4.0	2.2	1.4	1.0
^{238}U	35.7	9.0	4.0	2.2	1.4	1.0

O.4.5 Summary and Conclusions

The following concepts related to elevated areas should be considered during radiological survey activities:

- Although MARSSIM provides technical information on the measurement of areas of elevated radioactive material, the document is written to allow for flexibility in designing and implementing all components of radiation surveys.
- With respect to elevated areas, survey implementation and rigor should be commensurate with the risk from areas of elevated activity.
- The modeling approach used to calculate $DCGL_{EMC}$ should be generally consistent with the modeling approach used for evaluating the receptor dose or risk from the larger survey unit.
- If acceptable to the applicable regulatory agency, it may be appropriate to consider changes in the exposure scenario or exposure scenario parameters to account for the smaller area of radioactivity (e.g., changes in assumed occupancy times on the smaller area of elevated radioactivity, or elimination of certain pathways associated with the smaller area). However, care should be taken to understand how the applicable risk or dose modeling code used to calculate the $DCGL_{EMC}$ already considers the smaller area of elevated radioactivity to ensure that the dose is not underestimated.
- Areas of elevated activity may have different radionuclide ratios relative to the larger survey unit as a whole due to either redistribution of radionuclides or due to different events, which would lead to different assumptions for the design of radiation surveys for areas of elevated activity. As discussed above, radionuclide ratios also may change for sites following remediation. Spatial and temporal heterogeneity in radionuclide ratios should be considered during the design of Final Status Surveys (FSSs).
- When applicable, As Low As Reasonably Achievable (ALARA) criteria should be considered in determining whether elevated areas should be remediated during the Remedial Action Support (RAS) survey.
- It is always acceptable and conservative to assume the smallest area factor possible (i.e., 1). It is always acceptable and conservative to use the smallest area factor for any

[7] The values listed in **Table O.5** are for illustrative purposes only. Consult regulatory guidance to determine area factors to be used for compliance demonstration.

radionuclide, if the survey unit contains multiple radionuclides each with their own area factor.

O.5 Release Criteria for Discrete Radioactive Particles

With the installation in the mid- and late-1980s of very sensitive portal monitors, many nuclear power plants detected residual radioactive material on individuals and their clothing present as small, usually microscopic, highly radioactive particles having relatively high specific activity. These particles became known as “discrete radioactive particles” and sometimes “hot particles.” Discrete radioactive particles are small (usually on the order of millimeters or micrometers), discrete, highly radioactive particles capable of causing extremely high doses to a localized area in a short period of time.

In an attempt to prove compliance with requirements for discrete radioactive particles, some surveys have used the MARSSIM Elevated Measurement Comparison (EMC) process (see **Section 8.6.1**). However, the MARSSIM EMC process is not valid when instrumentation dose-to-rate conversion factor modeling assumes a “point source” as opposed to an “area source” or “plane source.” This violates the assumption inherent in the dose or risk model of an activity concentration averaged over some definable area. Therefore, it is not acceptable to use the MARSSIM EMC process when the distance to the detector is greater than three times the longest dimension of the area of elevated activity, as represented by:

$$d > 3L \tag{O-5}$$

where L is the estimated longest dimension of the area of elevated activity, and d is the distance to the detector.

To address discrete radioactive particles in surface soils or building surfaces:

- Include discrete radioactive particles as a consideration during the DQO process for MARSSIM surveys.
- When a regulatory agency sets requirements on the concentration of discrete radioactive particles in a survey unit, use the DQO process to develop a survey to assess whether requirements are met.
- When appropriate, apply ALARA by addressing discrete radioactive particles during the RAS survey.
- If discrete radioactive particles do not contribute significantly to dose or risk at a site, it is a reasonable assumption that they will not affect the outcome of a wide-area FSS. If an FSS fails due to discrete radioactive particles, investigate the reasons for survey failure (see **Section 8.6.3**).

O.6 Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) Sites

At UMTRCA sites, EPA’s Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings, in 40 CFR Part 192, are applicable. However, the technical requirements in these standards are not always consistent with some of the recommendations in MARSSIM. Specifically, the soil cleanup standards for ^{226}Ra and ^{228}Ra are specified as averages over an area of 100 square meters. (In the 40 CFR Part 192 rulemaking, an averaging area of 100 square meters was used as a reasonable footprint for a home. One goal of the 40 CFR Part 192 standards was to protect future homes from indoor radon, and the specified averaging area was a component implemented for the protection of health.) The rules at 40 CFR Part 192 do not establish specific requirements for small areas of elevated radioactive material. At sites where the uranium or thorium mill tailings standards are applicable, the following approach for FSSs is acceptable:

- A survey unit of no greater than 100 square meter sections of land should be used, consistent with the regulatory standards.
- The systematic sampling for performance of statistical tests, normally required under the MARSSIM approach are not required for each survey unit. Instead, compliance with the standard can be demonstrated through analysis of soil samples or composite soil samples from each survey unit, in conjunction with gamma radiation scanning or in situ gamma radiation measurements of each survey unit. When appropriate, gamma radiation scanning or in situ measurements correlated to soil sampling may be used in place of soil sampling.
- Survey units may be classified, as appropriate, and the percentage of the survey unit that is scanned may be adjusted accordingly for Class 1, Class 2, or Class 3 survey units.
- EMC criteria for small elevated areas of activity may be developed but are not required for the purposes of MARSSIM.

These minor modifications to the standard MARSSIM radiological survey approach are acceptable for those sites to which the UMTRCA standards are applicable.

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. Section 2121).

A_{min}: The smallest *area of elevated activity* that is important to identify using the *Data Quality Objectives (DQO) process*.

action level (AL): 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*.

ALARA: As defined in Title 10, Section 20.1003, of the Code of Federal Regulations (10 CFR 20.1003), ALARA is an acronym for "as low as (is) reasonably achievable," which means making every reasonable effort to maintain exposures to ionizing radiation as far below the dose limits as practical, consistent with the purpose for which the activity is undertaken, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations.

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 ($DCGL_{EMC}$)*.

area factor (A_m): A factor used to adjust the *derived concentration guideline level ($DCGL_W$)* to estimate the *derived concentration guideline level ($DCGL_{EMC}$)* and the *minimum detectable concentration* for *scanning surveys* in *Class 1 survey* units, wherein the $DCGL_{EMC} = DCGL_W \times A_m$. A_m is the magnitude by which the *concentration* of *residual radioactive material* in a small *area of elevated activity* can exceed the $DCGL_W$ while maintaining compliance with the *release criteria*.

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*, *byproduct*, or *special nuclear materials* 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 *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* is 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 extent and nature of *residual radioactive material*. *Characterization surveys* provide the basis for acquiring 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 *radiation surveys*) above the *derived concentration guideline level* ($DCGL_W$). Examples of *Class 1 areas* include: (1) *site areas* previously subjected to *remedial actions*,[1] (2) locations where leaks or spills are known to have occurred, (3) former burial or disposal *sites*, (4) waste storage *sites*, and (5) *areas* with *residual radioactive material* in discrete solid pieces of material and high specific *activity*.

Class 1 survey: A type of *final status survey* that applies to *Class 1 areas*.

[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 *derived concentration guideline level* ($DCGL_W$) and was remediated to demonstrate that the concentration of *residual radioactive material* is *as low as reasonably achievable (ALARA),* the remediated area might be classified as Class 2 for the *final status survey.*

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 (DCGL*$_W$). To justify changing an area's *classification* from Class 1 to Class 2, the existing data (from the *Historical Site Assessment [HSA]*, *scoping surveys*, or *characterization surveys*) should provide a high degree of confidence that no individual measurement would exceed the *derived concentration guideline level (DCGL*$_W$*)*. Other justifications for this change in an area's classification may be appropriate based on the outcome of the *Data Quality Objectives (DQO) 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 (DCGL*$_W$), based on *site* operating history and previous *radiation 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 [HSA]*, *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 (DQO) process*. Examples of *areas* that might be classified as Class 3 include buffer zones around *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 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., *Bq*/kg, pCi/g, or *Bq*/m^3) or *activity* per unit area (e.g., *Bq*/m^2 or dpm/100 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%, 90%, 95%) 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 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.

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, etc.) 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 *measurement* 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; e.g., if $\Pr(t > t_0) = 0.05$, 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 (3.7×10^{10} dps = 3.7×10^{10} *Bq*), which is approximately equal to the *decay* rate of one gram of ^{226}Ra. 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 prior to making a decision.

Data Quality Assessment (DQA): 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 (DQOs): Qualitative and quantitative statements derived from the *Data Quality Objectives (DQO) 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 (DQO) process: A series of logical steps that guides managers or staff to a plan for the resource-effective acquisition of environmental data. See also in this glossary *Data Quality Objectives (DQOs)*.

data usability: The scientific and statistical evaluation of data sets to determine if 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 (DQA).*

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* through *remediation* 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 confidence.

direct measurement: *Measurement* of radioactive material obtained by placing the detector near the surface or media 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 (DL): 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 (UBGR)* 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 (g/cm^3 or 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 (DCGL$_{EMC}$)*.

Elevated Measurement Comparison (EMC): This comparison is used in conjunction with the *Wilcoxon Rank Sum (WRS) test* and *Sign test* to determine if there are any *measurements* that exceed a specified value *derived concentration guideline level (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 performance 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*/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 release criteria.

fluence: The number of photons or particles passing through a cross-sectional area. The international standard (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.

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* is set equal to the *derived concentration guideline level* ($DCGL_W$), and the *lower bound of the gray region (LBGR)* is chosen on a site-specific. In *Scenario B*, the upper bound of the *gray region (UBGR)* is set equal to the *discrimination level*, and the *LBGR* is set equal to the $DCGL_W$.

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 (HSA): 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*. *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.

judgment measurement: *Measurements* performed at locations selected using *professional judgment* based on unusual appearance, location relative to known contaminated *areas*, high potential for *residual radioactive material*, general supplemental information, etc. *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 ($DCGL_W$)*. 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 (MDC)*.

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* corresponds is chosen to represent a conservative estimate of the concentration of residual radioactive material. For *Scenario B*, the *LBGR* corresponds to the *derived concentration guideline level ($DCGL_W$)*.

lower limit of detection (L_D): The smallest *concentration* of radioactive material in a *measurement* that will yield a net count (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 signal.

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.

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 to determine the level or quantity of radioactive material on a surface or in a *sample* of material removed from a media 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 Quality Objectives (MQOs): *Measurement Quality Objectives (MQOs)* are the specific analytical data requirements of the *Data Quality Objectives (DQOs)*.

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*.

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 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*.

minimum detectable count rate (MDCR): 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 Department of Defense, the Coast Guard, the 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.

NARM: Naturally occurring or accelerator-produced radioactive material, such as radium, and not classified as *source material*.

nonconformance: A deficiency in characteristic, documentation, or procedure that renders the *quality* of an item or activity unacceptable or indeterminate; nonfulfillment of a specified requirements.

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 (WRS) 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*.

NORM: Naturally occurring radioactive material, such as 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.

normal (gaussian) distribution: A family of bell-shaped distributions described by the *mean* and variance.

null hypothesis (H_0): See in this glossary *hypothesis*.

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 $(1 - \beta)$: 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., $(1 - \beta)$).

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 (DQIs) recommended for quantifying the amount of error in survey data. Precision represents that portion of the measurement method uncertainty due to random uncertainty.

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

Quality Assurance Project Plan (QAPP): A written document outlining the procedures a monitoring project will use to ensure the data it collects and analyzes meets project requirements.

quality control (QC): 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 (QMP): 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 (QA)* and *quality control (QC)*.

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}.

radiation survey: *Measurements* of radiation levels associated with a *site* together with appropriate documentation and data evaluation.

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 *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*.

ranked set sampling: A two-phase statistical sampling technique in which a subset of statistical *samples* is selected from a larger set of samples based on the rank of the *samples* with respect to the parameter of interest based on professional judgment or, in the case of MARSSIM, some type of field measurement.

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, chemical, radiological, and biological characteristics as the *survey unit(s)* being investigated, but which 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 (EPA), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), 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 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* 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 real time *measurement* of *areas* being remediated to determine whether efforts are effective and to guide further *remediation* activities.

remedy: The method that EPA 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 dpm/100 cm^2.

removal: As defined in *Technical Report on Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining*, EPA 402-R-08-005, 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*, ground water, 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.

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 one cubic centimeter of dry air at 0 degrees C and standard atmospheric pressure.

root mean square deviation (RMSD): 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 *samples* or *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 (SAP): A plan that provides a *process* for obtaining data of sufficient *quality* and quantity to satisfy data needs. The *SAPs* 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 (QAPP)*, which describes policy, *organization*, functional activities, *Data Quality Objectives (DQOs)*, and measures necessary to achieve adequate data for use in selecting the appropriate *remedy*.

scan-only survey: Survey in which *scanning* is used to both identify areas of elevated *concentrations* of *residual radioactive material* and estimate the average *concentration* of *residual radioactive material* in a *survey unit*.

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* ($DCGL_W$). *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 level of *concentration* of radioactive material in the *survey unit* is less than or equal to the discrimination 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 one. 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 (WRS) 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.

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 and/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.

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 *mean* zero and variance one.

standard operating procedure (SOP): 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, vegetation cover, *etc*.

subsurface soil sample: A *soil sample* that reflects the modeling assumptions used to develop the *derived concentration guideline level (DCGL)* for subsurface *soil activity*. An example would be soil taken deeper than 15 cm below the soil surface to support *surveys* performed to demonstrate compliance with 40 CFR 192.

surface residual radioactive material: *Residual radioactive material* found on building or equipment surfaces and expressed in units of *activity* per surface area (*Bq*/m^2 or dpm/100 cm^2).

surface soil: The top layer of *soil* on a *site* that is available for direct exposure, growing plants, resuspension of particles for inhalation, and mixing from human disturbances. *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 cm (6 in.) of soil (40 CFR 192), but it will vary depending on *radionuclide*, surface characteristics, *measurement method*, and pathway modeling assumptions. For the purposes of MARSSIM, *surface soil* may be considered to include gravel fill, waste piles, concrete, or asphalt paving.

surface soil sample: A *soil sample* that reflects the modeling assumptions used to develop the *derived concentration guideline level (DCGL)* for *surface soil activity*. An example would be *soil* taken from the first 15 cm of *surface soil* to support *surveys* performed to demonstrate compliance with 40 CFR 192.

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 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 data set.

TENORM: Technologically Enhanced Naturally Occurring Radioactive Material, such as naturally occurring radioactive materials (see *NORM* in this glossary) that have been concentrated or exposed to the accessible environment as a result of human activities, such as manufacturing, mineral extraction, or water processing.

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 (CEDE)* (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).

The Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP): A consensus *quality systems* document prepared by the Intergovernmental Data Quality Task Force (IDQTF), a working group made up of representatives from the U.S. Environmental Protection Agency (EPA), the Department of Defense (DoD), and the Department of Energy (DOE). Originally issued in 2005, the UFP-QAPP was developed to provide procedures and guidance for consistently implementing the national consensus standard ANSI/ASQ E-4, Quality Systems for Environmental Data and Technology Programs, for the collection and use of environmental data at Federal facilities.

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 *σ(x)* obtained from the propagation of uncertainty. See also in this glossary *standard deviation*.

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* ($DCGL_W$). For *Scenario B*, the *UBGR* is set equal to the *discrimination level*.

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*.

$\boldsymbol{W_r}$**:** The sum of the ranks of the adjusted *measurements* from the *reference area*, used as the *test statistic* for the *Wilcoxon Rank Sum (WRS) test*.

$\boldsymbol{W_s}$**:** The sum of the ranks of the *measurements* from the *survey unit*, used with the *Wilcoxon Rank Sum (WRS) 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 (WRS) 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 MeV of potential alpha energy. This value is approximately equal to the alpha energy released from the *decay* of progeny in equilibrium with 100 picocuries (pCi) of radon-222 (^{222}Rn).

$\boldsymbol{z_{1-\varphi}}$**:** The value from the *standard normal distribution* for which the fraction of the *area* less than z is $1 - \varphi$, or 100 × $(1 - \varphi)$ expressed as a percentage, and the fraction of the area of the area greater than z is φ , or 100 × φ expressed as a percentage.